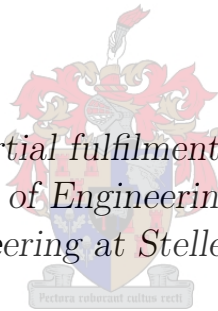


# Modelling, Design, Construction and Installation of a Daylighting System for Classrooms in Rural South Africa

by

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*Thesis presented in partial fulfilment of the requirements for  
the degree of Master of Engineering (Mechanical) in the  
Faculty of Engineering at Stellenbosch University*



Supervisor: Prof. A.B. Sebitosi

December 2014

# Declaration

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# Abstract

## Modelling, Design, Construction and Installation of a Daylighting System for Classrooms in Rural South Africa

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Thesis: MEng (Mech)

December 2014

Use of natural daylight for interior illumination of schools doesn't only contribute to the conservation of energy and the reduction of greenhouse gases emission but has also been found to enhance the performance of children in schools. In the case of most rural African schools the supply of electricity is totally absent and many classrooms operate with insufficient lighting levels especially during cloudy winter days. Many technologies have been suggested as ways to utilise natural daylight. The simplest and most commercially available is the passive zenithal light pipe (PZLP). The light at the end of an open pipe is characterised by sharp patches and shadows which result in uncomfortable and frustrating contrasts and glare for the user. In order to eliminate these imperfections the commercial tube is fitted with a diffuser. However this reduces the lux levels to very low values and renders the system unusable for high performance tasks such as reading and classroom illumination. Through the design and manufacture of a light collimator, the performance of the system has been improved from 178 lux distributed by a commercial diffuser to 370 lux distributed by a light collimator. This level is compliant with the South African Bureau of Standards regulation for reading. The next challenge however was the presence of glare patches of the order of 1000 lux. A range of reflector materials was tested but yielded similar disappointing results. Finally a breakthrough was achieved when a rough re-used aluminium cooking foil was discovered that totally eliminated these patches. The daylighting system (PZLP combined with a collimator) was installed in a classroom at Lynedoch, and its efficiency assessment has shown that the system is cost effective as it decreases up to 79 % of annual electricity consumption and has a payback period of ten years with a reduction of 1.6 tonnes of  $CO_2$  over the period. Furthermore, post installation tests and simulations were performed to test the stability of light levels for different altitudes of the sun and at dif-

*ABSTRACT*

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ferent times of the year. It was found that the system provided acceptable levels between 9 a.m. and 5 p.m. even during cloudy winters with minimal drift from the geometrical centreline of the collimator.

# Uittreksel

## Die Modelling, Ontwerp, Konstruksie en Installering van 'n Daglig Sisteem vir Klaskamers in die Platteland van Suid-Afrika

A. Ikuzwe

Tesis: MIng (Meg)

Desember 2014

Die gebruik van natuurlike daglig vir die beligting van die binnekant van skole dra nie net by tot die bewaring van energie en die vermindering van kweekhuis gasse nie maar verbeter ook die prestasie van kinders in die skole. In die geval van die meeste plattelandse skole in Afrika is elektriese krag onverkrygbaar. En is daar veral op bewolkte of wintersdae te min lig in die klaskamers. Daar is al baie voorstelle gemaak vir die gebruik van tegnologie vir optimum gebruik van daglig. Die passiewe zenital ligpyp (PZLP) is die eenvoudigste tegnologier en dit is ook geredelik kommersiaal beskikbaar. Die lig aan die einde van 'n oop pyp word gekenmerk deur skerp kolle, skaduwees, kontraste en fel lig wat vir die gebruiker ongerieflik en frusterend is. Om hierdie imperfeksies te elimineer word kommesiële pype vervaardig met 'n diffundeerder wat die lig versprei. Dit verminder egter die ligvlakke (lux levels) en veroorsaak dat die sisteem nie gebruik kan word in klaskamers waar daar gelees word nie. Die ontwerp en vervaardiging van die lig kollimator het die prestasie van die sisteem verbeter vanaf 178 lux wat deur 'n kommersiële diffundeerder versprei is tot 370 lux wat deur 'n lig kollimator versprei word. Hierdie vlak voldoen aan die Suid-Afrikaanse Buro van Standaarde se regulasies. Die volgende uitdaging was die teenwoordigheid van kolle helder lig (glare) van 1000 lux. 'n Hele aantal materiale wat kan weerkaats is getoets maar die resultate was teleurstellend. Daar was uiteindelik 'n deurbraak toe daar op 'n rowwe gebruikte aluminium foelie afgekom is wat hierdie helder kolle totaal elimineer. Die daglig sisteem (PZLP gekombineer met 'n kollimator) is in 'n klaskamer by Lynedoch installeer waar gevind is dat die elektriese krag gebruik met 79% per jaar gesny is, dat dit 'n jaar lank in gebruik kan bly en datv dit die  $CO_2$  met 1.6 ton tydens die periode verminder). Verdere installasies en toetse is vir verskillende ligvlakke en verskillende sonshoogtes

en seisoene is gedoen om sodoende die stabiliteit van ligvlakke by die verskillende hoogtes van die son en die seisoene gedoen. Daar is gevind dat gebruik van die sisteem lei tot aanvaarbare vlakke tussen 9  $\mu\text{m}$ . en 5 nm. selfs op betrokke wintersdae, met 'n minimale skuif vanaf die geometriese middellyn van die kollimator.

# Dedication

*This thesis is dedicated to the memory of my father Jean D. Kanoni*

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# List of Symbols

$D$	Diameter of the tube (mm)
$E_d$	Average exterior illuminance ( lux )
$E_{ob}$	Diffuse horizontal illuminance entering the light pipe ( lux )
$E_p$	Average internal illuminance at exit surface of the tube ( lux )
$E_s$	Direct horizontal illuminance entering the light pipe ( lux )
$L$	Length of the tube ( mm )
$N$	Numerical aperture
$N_R$	Reflection number
$P$	Input power (Watt)
$\eta_1$	Index of refraction of material 1
$\eta_2$	Index of refraction of material 2
$\eta_d$	Collection efficiency of the dome (%)
$\eta_t$	Transmission efficiency of the tube (%)
$\theta$	Angle of incidence (°)
$\theta_c$	Critical angle (°)
$\rho$	Reflectance of the material (%)
$\tau$	Transmittance (%)



# List of Abbreviations

<i>UV</i>	Ultraviolet
<i>IR</i>	Infra-red
<i>PVD</i>	Physical vapor deposition
<i>CIE</i>	Commission internationale d'éclairage
<i>TDD</i>	Tubular daylighting device
<i>BBRI</i>	Belgian building research institute
<i>GTM</i>	Greenwich mean time
<i>US</i>	University of Stellenbosch
<i>PZLP</i>	Passive zenithal light pipe
<i>CCDI</i>	Cape craft design institute
<i>LCP</i>	Laser cut panel
<i>TTE</i>	Tube transmission efficiency
<i>SABS</i>	South African bureau of standard
<i>SD</i>	Secure digital
<i>PC</i>	Personal computer
<i>SAD</i>	Seasonal affected disorder

# Chapter 1

## Introduction

### 1.1 Background

Installations such as residential, commercial, industrial and school buildings are some of the biggest consumers of energy. The electricity utilized to provide them with light forms a major part of the power consumption of society (globally, electric lighting accounts for about 20 % of all the electric energy consumed)(Bill, 1999). In these buildings electricity is often used during the day even though the sun is shining outside. According to the South African Department of Energy, lighting accounts for up to 21 % of the total electricity consumed in the commercial buildings and contributes to 21 % of the total greenhouse emissions. Figure 1.1, shows electricity consumption in South Africa.

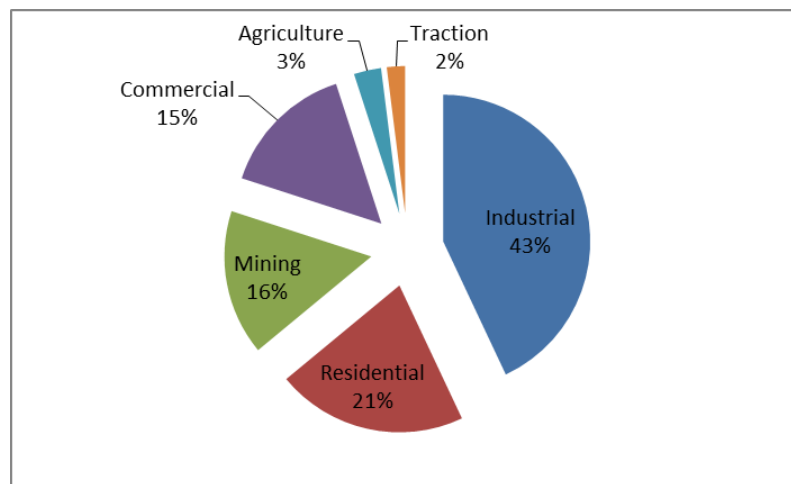


Figure 1.1: Electricity consumption in South Africa

(Bill, 1999)

The use of solar energy has been recognized as a leading intervention for

the conservation of energy (Tregenza and Loe, 1998). While many solar energy systems have been developed for heating, distillation and production of energy, little or no attention has been paid to their ability to provide light where large quantities of electricity are being used during daylight hours. Given the current dependence on fossil fuels for electricity generation and a concern for the environment, people are becoming conscious of the consumption of energy and wondering how this natural, clean, free for taking and environment-friendly energy may be harvested, concentrated and distributed inside to replace most of the electrical lighting that is consumed today.

Daylight is an effective source of light, and sunlight and skylight are brighter than fluorescent and incandescent sources. Daylight provides the same quantity of visible light as an electric light source will supply with less heat. Sunlight luminous efficacy ranges from 102 to 116 Lm/W depending on solar altitude and for skylight the average is 150 Lm/W, compared with the range of 45 to 95 Lm/W for fluorescent luminaire and less than 25 Lm/W for incandescent sources (Hopkinson R. G. and Longmore, 1963). Due to the high efficacies of daylight, successful daylighting system may decrease the cooling load of a building which leads to a further decrease in energy consumption, provide energy, economic savings, environmental and aesthetic advantages.

Many countries in Sub-Saharan African region are having difficulties supplying sufficient electricity for schools in rural areas. This leads to weak human and institutional capacity development. Good daylight has been shown to be closely associated with improvement in student performance and the promotion of better health. It also helps significantly to improve the aesthetics and the physical character of the learning space. Also a global sustainable outcome (i.e greenhouse emission reduction) can be obtained by reducing the reliance on non-renewable energy sources and relying on solar and sky radiation.

Although daylighting systems are an obvious choice due to the climate of South Africa, the majority of schools were not designed with daylighting as a top priority. A need exists, therefore, to find an efficient means of improving the daylighting of existing schools. The proposed solution of interior daylighting improvement for existing schools in this study is the passive zenithal light pipe. The passive zenithal light pipe is one of the systems capable of harvesting natural light in the interior room space. It is capable of collecting, transporting and distributing sunlight over long distances within a building. Sunlight is collected by the top dome and transmitted down the tube through multiple specular reflections. The diffuser is fitted at the bottom end of the tube, usually to the ceiling to allow the distribution of the daylight into interior room space.

It is acknowledged that a poorly designed daylighting system can increase the energy consumption of a building by increasing the interior heat summer and provide irritation to occupants. Careful design of a daylighting is therefore required to deliver any of the anticipated benefits from its use.

## 1.2 Daylight

Daylight or the light of day is natural light from the sun, it is a mixture of all direct and indirect sunlight outdoors during the daytime. Daylight is the key source of all renewable energy and is an easily accessible and inexhaustible resource with vast potential. There are two forms (Harvey, 2002) of available natural light; direct sunlight and diffuse light from the sky.

Direct sunlight is straight from the sun and can thus project shadows. Sky diffuse or indirect sunlight comes from the sky not the sun, it is from clouds or blue sky. The amount of sky diffuse attaining the surface depends on the type of cloud, the elevation angle of the sun and the amount of reflected surface radiation that is reflected downwards again. The use of these two forms of daylight as a primary or supplementary means of illuminating the inside of buildings during the day is termed daylighting. Daylighting can create a visually stimulating and productive environment for occupants of the building, while reducing energy costs. Due to the relatively high efficacies of daylight, a successful daylighting system can:

- Reduce the cooling load of a building which contributes to the further decrease in energy consumption,
- Provide both energy and economic savings,
- Provide environmental and aesthetic advantages over sole reliance on electric lighting.

The primary historical daylighting device is the window, which at its most basic is simply an opening in the building fabric (Muneer T. and Kombezidis, 1997). To day the window is still the dominant source of daylight globally. However, for a variety of reasons the vertical glazing unit is not always an ideal source of illumination. Direct sunlight is often not a good source of illumination in the built environment as its intensity and directional nature generates glare for building occupants. However, diffuse light does not penetrate far into rooms fitted with windows. Therefore, the challenge is to develop means of utilising both direct and diffuse natural light in buildings while maintaining and improving occupant visual comfort, particularly at greater distances from the external walls.

### 1.2.1 Source and availability

Sunlight is the primary source of energy to the earth's surface that can be exploited through different processes both natural and synthetic. In principle, all types of energy in the world (oil, coal, natural gas and wood) are solar in origin (Ander, 2001). Similarly, wind and tide energy are of solar origin since they are caused by differences in temperature in various regions of the earth.

The main advantage of solar energy compared with other alternative forms of energy is that it is clean and can be provided without environmental pollution and is available almost anywhere.

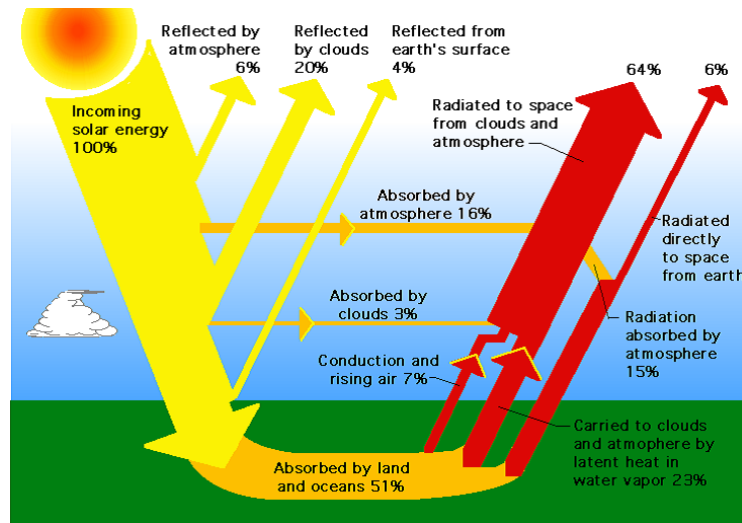


Figure 1.2: Solar energy received at the earth's surface  
(Hopkinson R. G. and Longmore, 1963)

The daily and seasonal motions of the sun with respect to a particular geographical situation on the earth generate a predictable pattern with regard to the amount and direction of available light. Superimposed on this predictable pattern are variations due to changes in the weather, temperature and air pollution. The solar energy reaching the earth's surface is comprised of 40 % (Muneer T. and Kombezidis, 1997) visible radiation, the rests is ultraviolet (UV) and infra-red (IR) wavelengths. When absorbed, virtually all the radiant energy from the sun is converted to heat. The amount of visible energy in the solar spectrum varies with depth and the condition of the atmosphere through which the light traverses. On a beautiful summer day, levels of light outside might be as much as 100,000 to 120,000 lux on level surfaces, while on a dark winter day they could be around 4000 - 5000 lux (due to the location latitude) (Ander, 2001).

### 1.2.2 Daylight and energy conservation

Lighting is an important part of the monthly energy consumption and costs especially for commercial and industrial buildings. The use of daylight may realize considerable savings. Research done (Zhang and Muneer, 2000b) has shown that savings of 20 % to 40 % are realizable for office buildings that use daylight effectively. Another significant benefit of using daylight is that it is

totally free and clean, which makes it one of the most cost effective means of reducing electricity consumption. Therefore, applying more efficient daylighting design in buildings will contribute to energy conservation and environmental improvement.

### 1.2.3 Controlling and evaluating daylight

Daylight varies in both intensity and quality from moment to moment, and the level of variation desirable and tolerated depends on the particular task or requirement. Lighting needed may be strict for some users, but are softer in many applications. However, to ensure good lighting, there are three factors which should always be taken into consideration; quantity, light quality and distribution.

- **Illumination level**

When assessing a daylighting conception, it is required to assess the balance of levels of luminance in all space. Surface luminance balances and illuminance levels are important factors in overall lighting quality and mood. For visual comfort the luminance ratios in the immediate vicinity are not expected to be less than 1/5, nor greater than five times the luminance of the task (a ratio of 5:1). The general surrounding area should not be less than 1/10 or greater than 10 times the luminance of the task (a 10:1 ratio) (Deepa and Jason, 2006). An intensive source of light (sunlight) may cause severe glare that can be both irritating and debilitating for a user's task. For this reason the control of the sunlight entering the space requires careful design of daylighting. Table 1.1 represents the recommended illumination levels by the SABS (South African Bureau of Standard).

- **Daylight factor**

Daylight factor is defined as the ratio of the internal illuminance to the external diffuse illuminance available simultaneously, it is generally expressed as a percentage. Daylight factor is split into three components; the sky component, the externally reflected component and the internally reflected components. The sky component is the ratio of illuminance at any given point that is received from a sky of known luminance distribution to the horizontal illuminance under an unobstructed sky hemisphere. The external and internal reflected components are respectively the ratios of the illuminance received after reflections from external and internal surfaces to the horizontal illuminance under an unobstructed sky hemisphere. It is limited to skylight transmission (Hopkinson R. G. and Longmore, 1963).

Table 1.1: Recommended illumination by the SABS (South African Bureau of Standards) (Jenny, 2013)

Illuminance Lux	Type of interior area task or activity					
	Office	Pharmacy	Restaurants	hotels Warehousing	Hospital	School
100					Sickroom and warehouse	
150		Raw material storage	Kitchen	Small material, packing and dispatch		
200		Laboratories and testing	Reception and porter's desk	Inactive storage and automatic stores		Classrooms and tutorial rooms
300	Conference, reception room, and circulation		Dining room, function room and bars			
500	Writing, reading and data processing	Manufacturing, grinding, granulating, etc.			Medical examination room	Lecture hall, Practical rooms and laboratories
750				Loading bays and large material		Technical drawing, art and craft rooms
1000					Operation room and emergency treatment	

Table 1.2: Recommended daylight factor  
(Muneer T. and Kombezidis, 1997)

Area		Average light factor(%)
Office	detail work	4
	Corridors	0.5
Residential	Kitchen	2
	living room	1
	Bedroom	0.5
Schools	Classroom	2
	Art room	4
Hospital	Wards	1
	Waiting room	2

Daylight factor is useful in figuring out lighting requirements for interior use, especially if you seek to maximize natural light for economical or environmental reasons. Like other light measurements the internal illuminance is normally taken at the horizontal working plane level (Harvey, 2002).

$$\text{Daylight factor} = \frac{\text{internal illuminance}}{\text{external illuminance}} \times 100$$

#### • Glare

Glare is the undesirable effect of a source in the observer's field of view with an intensity much greater than that to which the eye is adapted. It is characterised by visual discomfort and is generally divided into two categories (Steven, 1999), disability and discomfort glare. Disability glare is defined as sufficient to impair vision. Within buildings it predominantly occurs in poorly lit interiors that contain specular reflections of the sun in the occupant's field of vision. And discomfort glare describes sensations of distraction, annoyance and pain that may not necessary impair vision. The factors influencing discomfort glare are; source luminance, apparent size of the source to the observer, position of the source to the observer's field and adaptation conditions in the immediate surrounds.

Sunlight can easily be a source of unwanted glare. Clearly in a daylighting situation the admission of sunlight to an interior must still be appropriately controlled. Reduction of glare due to sunlight is generally achieved by a shading device, low-transmittance glass and a daylighting system that relies on a diffusely reflecting ceiling to act as secondary source.

### 1.2.4 Some terminologies used in daylight

- Light: is part of the electromagnetic spectrum which is perceived by our eyes. The electromagnetic spectrum perceived by our eyes (visible light)



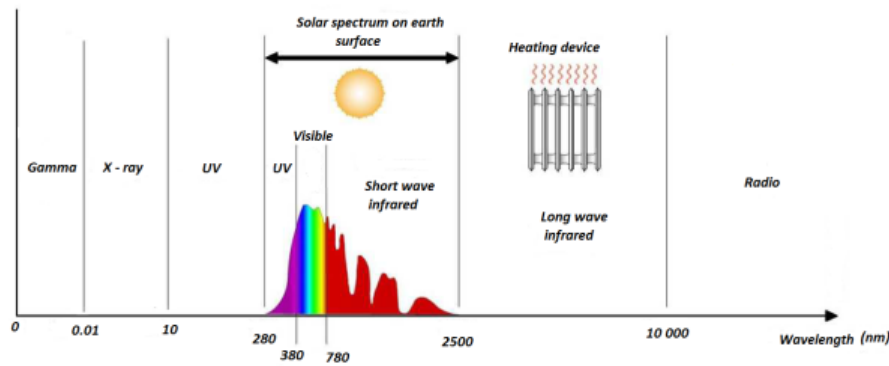


Figure 1.3: Electromagnetic spectrum of light

(Hopkinson R. G. and Longmore, 1963)

is a small group of wavelength between 380 nm ( $1\text{nm} = 10^{-9}$ ) and 780 nm.

- Natural light: is light which illuminates the earth emanating from celestial bodies.
- Sunlight: is the direct solar radiation component of natural light.
- Skylight: is the diffuse sky radiation component of natural light.
- Refraction and Reflection: light as wave motion undergoes reflection and refraction. Light can travel through space it does not need a medium to propagate through. When light falls at surface (water, air, etc.), refraction occurs because the speed of light in space is the highest so when it enters in another medium the speed decreases and it refracts near to the medium and some of the light is absorbed in order to give medium its colour and some of the colours of light beam are absorbed and the rest of the light spectral is reflected so that we can see the medium. Angle of incidence (angle light ray made with the horizontal surface of medium) is equal to the angle of reflection (angle which reflected ray made with the horizontal surface of medium)

- Total internal reflection: occurs when light attempts to pass from a more optically dense medium to a less optically dense medium at an angle greater than the critical angle (critical angle is the angle of incidence that produces an angle of refraction of  $90^\circ$ ). When this occurs there is no refraction, only reflection.

### 1.2.5 Light measures

There exist a various metrics commonly used when describing light.

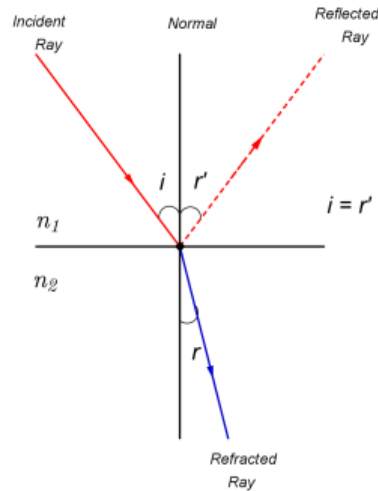


Figure 1.4: Reflection and refraction

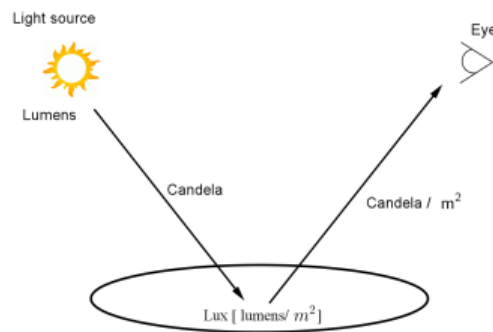


Figure 1.5: Various ways to measure light, and the different units in which it is measured in

- Illuminance: describes the amount of luminous flux incident on a surface. It reduces by the square of the unity of the distance. It is measured in lux (Lx).
- Luminance: is the only parameter of basic light which is seen by the human eyes. It pointed the luminosity of a surface depends mainly on its reflectance.
- Luminous flux: is the full flow of a light source. It is the power radiated estimated depending on the sensitivity of the human eyes. It is measured in lumen (Lm).
- Luminous intensity: describes the quantity of light which is radiated in a certain direction. It is a useful measure for lighting elements directive such as reflectors. It is measured in candelas (Cd).

- Luminous efficacy: it is the ratio of light flux emitted by a lamp to the power consumed by the lamp. It reflects the efficiency of energy conversion of electrical energy in the form of light.

Table 1.3: Overview of light quantity and units (Tylor, 2008)

Quantity		Unit	
Name	Symbol	Name	Symbol
Luminous energy	$Q_v$	lumen second	lm-s
Luminous flux	$\Phi_v$	lumen (= cd. sr)	lm
Luminous intensity	$I_v$	candela (= lm/sr)	cd
Luminance	$L_v$	candela per square metre	$cd/m^2$
Illuminance	$E_v$	Lux (= $lm/m^2$ )	lx
Luminance emittance	$M_v$	Lux (= $lm/m^2$ )	lx

### 1.3 Objectives

The main objective with this work is to provide a set of guidelines and recommendation for the application of daylighting technology for a classroom at the Sustainability Institute at Lynedoch. The aims of the researcher are presented below:

- To conduct a literature study on daylighting systems in order to obtain a basic grounding in the subject matter and familiarise oneself with methodologies with which the present work may be compared,
- To study and do evaluation of technologies that could be used, then compare the performance of the selected models,
- To design, construct, install, test and further improvement of selected model and specifically to increase its efficiency in order to meet several criteria; increase daylight levels in buildings, contribute to the reduction of energy consumption, create healthier working environments and be a cost effective solution.

### 1.4 Problem formulation

Nowadays, there exist many innovative daylighting technologies which could be used to enhance natural illumination for buildings that use more electric light during the day such as schools, industrial buildings, etc. There are, however, still a number of shortcomings with the application of these technologies. This research will therefore seek to answer the following questions.

- How effective are they in terms of their performance?

- How can their efficiency be improved?
- Can these technologies introduce to buildings the benefits of natural illumination that can contribute to the improvement of aesthetic and physiological aspects, workplace health and the productivity of the environment?

## 1.5 Evaluation methods

In order to accomplish the afore-mentioned aims, a number of different methods will be used. These include a literature review and scale modelling. The literature review is necessary in order to get acquainted with the subject area and gain an insight into what has been done to date. The scale model will be used to assess the effectiveness of the prototype light pipe. Illuminance measurement will be taken for quantitative analysis. Two types of testing will be performed under sunny and sky conditions and a lux meter/data-logger instrument will be used. Then the field testing of the improved daylighting system.

## 1.6 Research outline

Daylighting systems are described further in chapter 2, where the methods and existing technologies are summarised. An assessment is given of the benefits and limitations of available systems. In chapter 3, the theory of an innovative solution technology (passive zenithal light pipe) consisting a mirrored light pipe is discussed and this forms the basis of the research. In chapter 4, the methodology used to test the performance of the passive zenithal light pipe under sunlight (direct light) and skylight (diffuse light) conditions is introduced. Scale model testing for the collection, transmission and distribution efficacy of daylight through the light pipe is studied. The design, fabrication and test analysis of the light output device (light collimator) is presented in chapter 5. In chapter 6, the field test site is presented. Discussion and conclusion of the thesis are outlined in chapter 7.

# Chapter 2

## Daylighting Systems

### 2.1 Introduction

Daylighting refers to the utilisation of sunlight and skylight as a primary or supplementary means of illuminating the inside of buildings during the day. There are many reasons for introducing daylight into buildings, here are some reasons:

- The quality of natural light, its spectral composition and variability results in a better illuminated environment than electric light does,
- Daylight provides psychological and physiological advantages that improve the performance of people. This is not obtainable with electric lighting or windowless buildings,
- Better energy efficiency is obtained when replacing the demand for electricity during the peak hours of the day by the use of solar energy,
- An overall sustainable result can be obtained by reducing the reliance on non-renewable energy sources and relying on solar and sky.

### 2.2 Methods of daylighting

There are three common ways to introduce daylight in depending on the location of the area which the system has to illuminate. These ways are top-lighting, side-lighting and core-lighting (Karlen and Benya, 2004).

#### 2.2.1 Top lighting

Top-lighting is a way of introducing daylight in the building through an opening in the roof plane of the building. This is the simplest form of natural lighting and is relatively unaffected by the orientation of the site and adjacent

buildings. Below are several classic prototypes for top lighting (Karlen and Benya, 2004):

- Skylights: are openings in the roof that let daylight in to illuminate the room. They can be horizontal or sloped. Horizontal skylights introduce more light and heat during the summer but sloped skylights (preferably towards the south ) collect light more uniformly throughout the year. Due to their position (top) in the building which permits them to view a large part of the sky dome, skylights transmit a high level of illumination. To control the introduction of direct sunlight through skylights diffusers are necessary. Skylights are a passive technique to collect daylight and transmit it indoors, but they can also be made active by combining them with heliostats.
- The single clerestory: collects direct as well as indirect sunlight and introducing them through a vertical clerestory window. Depending on the adjacent roof, some of the light may be reflected downward by the ceiling into the space. However, depending on site orientation, the relatively high percentage of direct light can be glaring.
- The sawtooth single clerestory: collects both direct and indirect sunlight and introduces them by bouncing a high percentage off. The adjacent slanted ceiling increases the amount of downward light and can minimize the amount of direct light. If the sawtooth glazing faces north, it can be an excellent source of natural light for a large interior area.
- The monitor or double clerestory: also admits plenty of daylight, especially in buildings where solar orientation or weather do not permit the sawtooth or other more unusual designs. With proper choice of glazing and overhang, a monitor can produce exceptionally balanced and comfortable daylight.

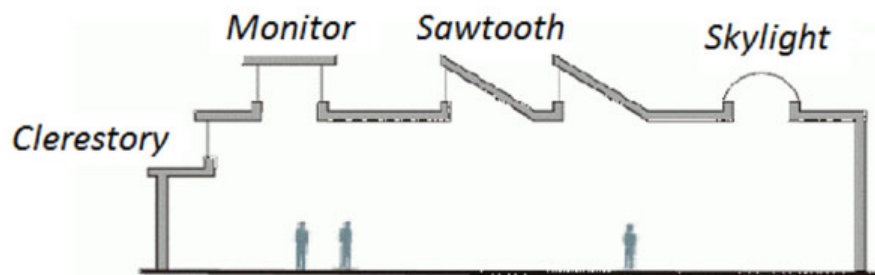


Figure 2.1: Top-lighting methods

### 2.2.2 Side lighting

Side lighting is the most popular method of natural lighting and uses vertical fenestration (usually windows) to bring natural light into the interior. Contrary to top lighting, side lighting tends to bring light that may be much brighter relative to the room surfaces, and sometimes causes glare. However, the desirable view provided by windows usually makes glare an acceptable side effect. It provides views to the exterior which is one of the most important psychological benefits of daylighting. To make the most of windows they should be placed high on the wall to allow light to penetrate deep into the room. They should also be widely distributed and preferably be placed on more than one wall in a room. This makes the daylight more evenly distributed and makes the contrast lower since there are more light sources. Windows should be placed next to interior walls, which then act as low-brightness reflectors that spread the daylight. This also reduces glare from the window, which lowers the contrast (Karlen and Benya, 2004).

### 2.2.3 Core lighting

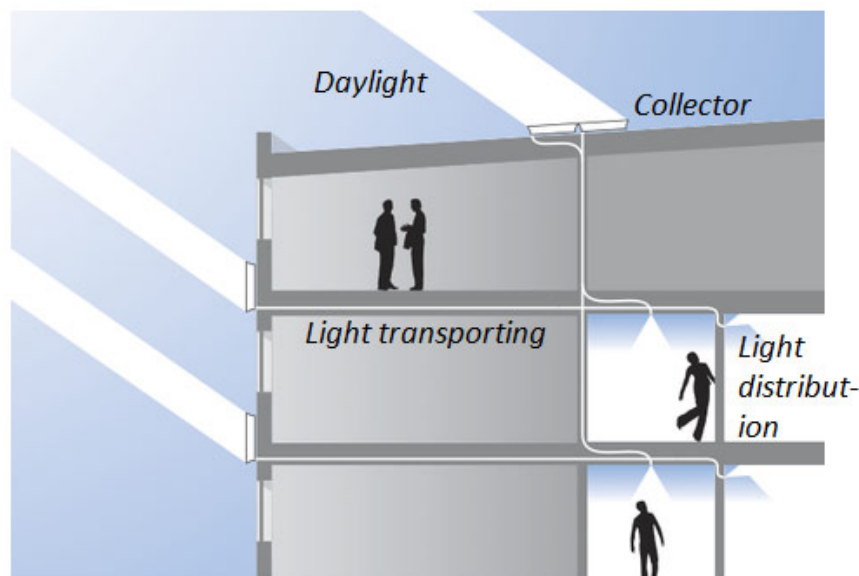


Figure 2.2: Core-lighting method

Core-lighting is a daylighting system which directs sunlight into the core of the building, these cores cannot be illuminated by top or side lighting because they are not adjacent to the building. This method consists of a light collector, the transport path of the light and ways of light distribution (dispersion within the area to be lighted). The light collector is placed outside the area for

collection of the sunlight from the sky. The collector of the light needs to be guided to the area that requires illumination and then distributed within the area to be illuminated (Brian, 2011). There exist numerous ways of collecting, transporting and distributing daylight into the core of the building and some of them are discussed in chapter 3.

Table 2.1: Comparison table of daylighting methods

Method	Climate	Attachment	Drawback	Cost
Top-daylighting	Overcast sky	Roof window and skylights	Glare, excessive brightness, high contrast, heat gain in summer and heat loss in winter	Medium
Side-daylighting	Overcast and clear sky	Wall window	Glare, excessive brightness and high contrast	Low
Core-daylighting	Clear sky	Not adjacent to the building envelope	High cost factor	High

## 2.3 Traditional daylighting systems

Daylighting systems known as traditional are windows and skylights. The window is the most widely used daylighting device in building. The main function of a window as mentioned before is to provide an outside view and to permit light penetrate the interior of a building in such quantity and with such distribution that it provides satisfactory interior lighting results. Skylight on the other hand can be considered as horizontal or sloped windows on the roof of a building. They work effectively as daylighting in the perimeter zone of a building, and also allows sunlight to penetrate the interior of the space.

Both windows and skylights can be classified as conventional passive daylighting devices. The main feature of passive solar devices is that they use the form and fabric of building to admit, store and distribute solar energy for heating and lighting without additional energy input and consumption. The design and application of windows and skylights for daylighting are limited in many ways (Veronica, 2006):

- The window performance is greatly constrained by the external natural and man-made obstructions,
- Windows are not applicable to interior rooms within large buildings or corridors between rooms where daylight cannot reach,



- In a deep building without roof-lights daylighting is restricted to areas near the window.

### Daylight illumination through windows in a classroom at Lynedoch

In November 15<sup>th</sup>, 2012 a study on the performance of the traditional daylighting system (window) in distributing sunlight to the interior of the building was done, at the Sustainability Institute at Lynedoch in the energy classroom. Daylight is part of the lighting used in this classroom, it is let indoors through windows as can be seen in figure 2.3. Direct sunlight that penetrates indoors through windows often produces an unpleasant glare on work surfaces, making it difficult to work or view a computer screen. In order to control this problem of over illumination, windows blinds are being used however this affects the quality of lighting in the classroom and therefore artificial electrical lighting becomes necessary.

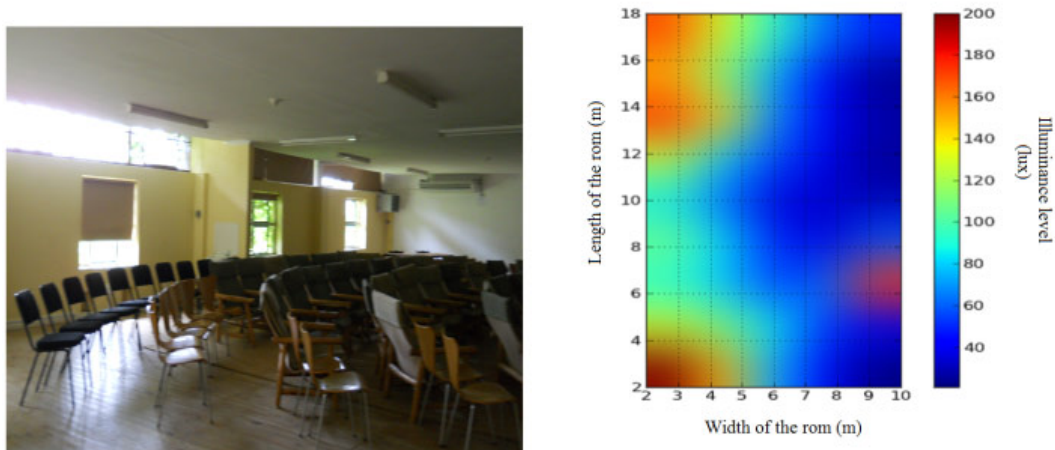


Figure 2.3: Natural illumination in the classroom at the Sustainability Institute (Lynedoch)

When the illuminance levels were measured (on 15<sup>th</sup> November, 2012 between the hours of 13h00 -13h30) in that room, it was found that they varied from 20 lux to 200 lux (high illuminance closer to windows, low illuminance far from windows). Careful measurements were recorded for the luminous flux within the building. The measurements were taken with an ISO-TECH-1332A digital illuminance meter. These measurements were recorded at desk height level. 45 points were around the room of length 18 m and width 10 m.

## 2.4 Innovative daylighting systems

Innovative daylighting systems are optical devices able to bring more daylight into interior areas of large buildings than what traditional daylighting system can bring. There are two major groups of innovative daylighting systems (Callow, 2003):

- Light guide systems
- Light transport systems

### 2.4.1 Light guide systems

Light guide systems bring direct and diffuse natural light into the interior of the room without glare and overheating effects. There are several different systems, and there are similarities with regard to their general performance, position in the building, or means of redirecting the light. They are grouped as vertical elements, horizontal elements and parabolic collectors. Light guide systems may increase daylighting levels at the rear of the room but, such systems don't have ability to illuminate the core of deep-plan buildings (Veronica, 2006).

#### 2.4.1.1 Vertical elements

Vertical elements include devices that are usually placed on the top of windows. They redirect the light deeper into the room by means of reflection and refraction. Their most important advantage is their simple integration into the building design (Veronica, 2006).

- **Prismatic panels**

The prismatic panels are covered by prisms on one side, while the other is flat. The prisms repel the direct light for reflection toward the outside and inside diffuse scattered light by refraction. The panels are available with four different (5, 28, 36 and 45 degrees) prisms which differ in the angles of refraction. They are mainly made of acrylic material or polyester and prisms are obtained by incisions or for modelling which consists of the impression of the prisms in the material. The prismatic films are very thin and light, and to protect them from scratches or dust, they must be enclosed between two sheets of ordinary glass (Ruck and Smith, 1982).

- **The angular selective skylight**

The angular selective skylight is made by the incorporation of a triangular or pyramid configuration of a laser cut panel (LCP) within a skylight to deliver the transmission of angular selective. Much of the low angle sunlight is redirected by the laser cut panels while most high elevation light is rejected,

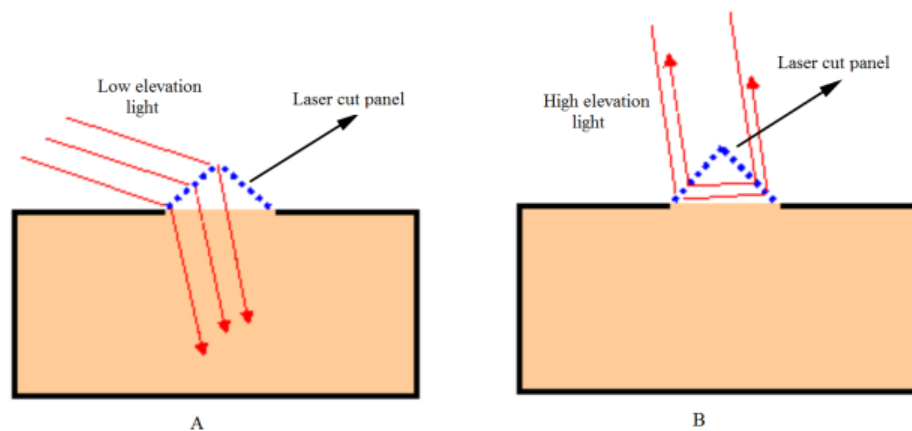


Figure 2.4: Angular selective skylight

thereby reducing overheating near noon. The performance of the angular selective skylight depends on the cut spacing of the laser cuts in the panel, the tilt angle of the pyramid or the triangle configuration of the panels, the well depth of the skylight, the time of day and season and the sky conditions (Pearce, 1999).

In figure 2.4 A, a lower elevation light is intercepted and redirected down into the building. Also, high elevation light is redirected by one panel across to the other panel and out of the building in figure 2.4 B.

#### 2.4.1.2 Horizontal elements

This group includes devices formed by one horizontal baffle, or systems consist multiple horizontal or sloping slats. Their most important benefit is the protection against glare, but there have problems with dust accumulation, and therefore the devices require maintenance. These systems give the best performance at position close to the window (Veronica, 2006).

- **Light shelf**

A light shelf is a passive architectural device that allows natural light to enter deep into a building, it might be exterior or interior. External and internal light shelves mounted on the south and west-facing windows can redistribute light throughout a building, providing natural brightness. The light shelf bounces visible sun light up towards the ceiling, which reflects it down deeper into the interior of a room. The light shelves should be mounted horizontally for best performance. The surface of the shelf must be highly reflective so the angle that the sunlight is reflected onto the ceiling will be equal to the angle of incidence of the incoming sunlight. The ceiling should be painted with a reflective paint in a light colour to bounce the light back down onto the work area (Derek, 2006).

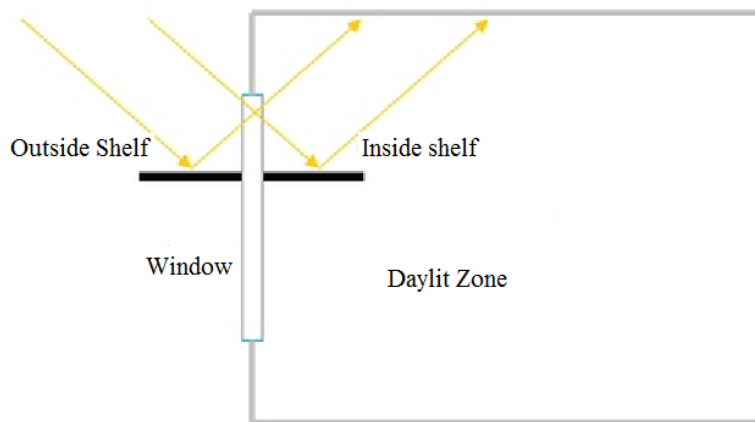


Figure 2.5: Light shelf

### 2.4.1.3 Parabolic elements

The principle of parabolic element is based on the compound parabolic collector. A specific geometric form accepts light from a specified angular range of the sky, and light is then redirected deeper into the room. The devices were designed for sunny places or for overcast sky condition such as anidolic systems. The major drawback of anidolic system is their integration to the building if they are not considered earlier in the design process (Kleindienst and Andersen, 2008).

- **Anidolic system**

An anidolic lighting system is a lighting system that uses non-imaging optical (anidolic) components such as parabolic or elliptical mirrors to capture exterior sunlight and direct it deeply into rooms, while also scattering rays to avoid glare. The system is composed of three essential parts (Scartezzini and Courret, 2002):

- Non-imaging optical zenithal collector designed and placed in front of the light guide to collect and concentrate daylight at the entrance of duct,
- Anidolic ceiling for optimal distribution of captured light to target area,
- Optimal integration into the building facade.

Most of the light guiding systems work with the direct component of daylight, whereas the anidolic collector can collect and redirect diffuse light. Consequently, their orientation is very important. Additionally, for optimal performance thought the day and year, they may need to track the sun's position, or at least change the position seasonally. However, these systems are incapable

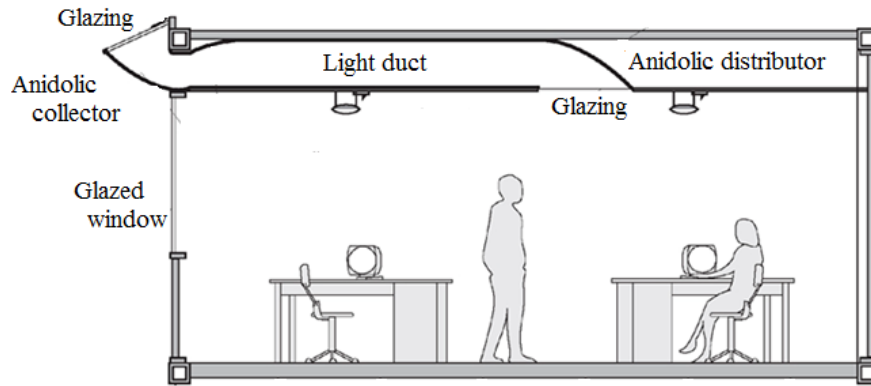


Figure 2.6: An anidolic integrated ceiling

of illuminating the core of deep-plan buildings, and other daylighting systems are required (Greenup, 2004).

## 2.4.2 Light transport systems

Light transport systems are capable of collecting, transporting and distributing sunlight over long distances into a building, and are generally called light pipe. They are mostly composed of three major components (Ayers and Carter, 2002); the collector, transportation and distribution components.

### 2.4.2.1 Light collector

The light collector is generally consists of reflective or refracting devices. Its main objective is to capture sunlight and direct it through a small aperture into the interior. Collecting and conveying daylight to a specific location can be achieved by active (system of collecting sunlight using automatic and moving parts devices to follow and track the sun) or passive ( a stationary system which doesn't follow or track the sun ) systems (Audin, 1995). Light collection is achieved either by redirection of sunlight or by concentration of light. Light collection is one of the most important factors in determining the performance of the light transport system. Therefore, considerable effort is required to select the most appropriate solution. The selection of an active or passive system will depend on the space available in the building, lighting conditions of the location, budget, and limitations on the angle of acceptance of the material used as a light pipe (Mirkovich, 1993).

### 2.4.2.2 Light guidance for light transport systems

The general classification of light guidance systems depends on the material used to transport the light (mirrored pipe, lenses, prismatic guides, fibre optics, etc.). Different materials have different optical properties and depending on

the material, light can be transported by four different methods (Tunnacliffe and Hirst, 1996):

1. Beam/lens
2. Hollow mirrored pipe
3. Hollow prismatic pipe
4. Solid core

In addition, the optical properties of the material define the best angle of acceptance for the optimal performance of the light pipe. Light transport materials that require a collimated beam will result in more complicated collection systems (Mirkovich, 1993).

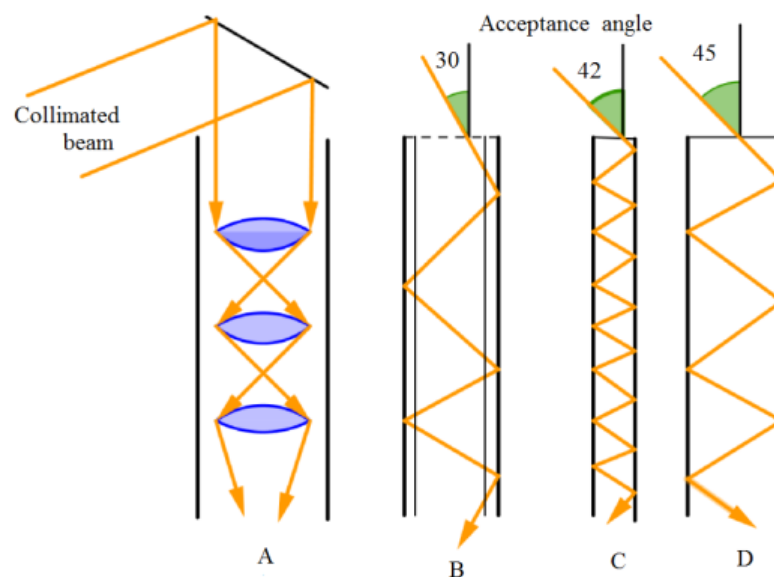


Figure 2.7: Different methods of light transport system. A: lenses, B: hollow prismatic pipe, C: light rods, D: mirrored light pipe.

#### • Lenses/beam

A lens system initially requires an active collector to concentrate and collimate light. The converging refracting surface of the first lens converges the light to a focal point, from where the light can diverge again (Tunnacliffe and Hirst, 1996). Successive lenses will be spaced at distances so as to capture the diverging light and re-converge it to a focal point, thereby maintaining a collimated light. Each individual lens transmits an image of the preceding lens to the next (Bennet and Eijadi, 1980). The number of lenses required and

their spacing is a function of the focal length of lenses. The distance that they can reach depends on their efficiency. Light loss is caused by optical processes, lens absorption and scattering (Eijadi, 1983).

These systems have two drawbacks that limit practical application. First, light-redirecting equipment such as lenses and mirrors tend to be more expensive than the other methods. Second, there are high levels of light loss in the optical processes. Whilst a clear lens can transmit a maximum of 92 % of light, losses increase with dirt deposition on surfaces. Efficiency also depends on accurate alignment, so that in systems consisting of several components, losses due to misalignment become significant.

- **Hollow prismatic light guides**

The system of a hollow structure is made of transparent acrylic plastic, with prism-shaped external facets on the wall. The external facets behave like mirrors by the process of total internal reflection. When a light ray strikes the inner wall of the pipe, some of the light will be reflected back to the air space and some transmitted into the wall material (Brown and Curzon, 1984). Light rays that continue into the wall material will by total internal reflection strike the facets of the outer wall, and be redirected back to the inner tube and air space. Light trapped within the pipe material will continue to propagate down the pipe.

The devices redirect light down the inside of the guide when the prisms are orientated parallel to the axis provided that the incident light does not exceed  $27.5^\circ$  (Aizenberg, 1997) to the axis of the pipe. Overall reflectance is of the order of 98 %. In theory, all light will be reflected by this process, but irregularities in the film cause a small proportion of light to exceed the maximum angle and leak out of the pipe (Aizenberg, 2000).

- **Hollow Mirrored guides**

In hollow mirrored pipes, light is sent indoors through the tube from the source to the output aperture by a number of multiple specular reflections at the interior wall surface of the pipe (Whitehead, 1994). Light transmission depends on the input angle of the incident light, the proportions of the tube in terms of the ratio of length to the cross-section area and on the reflectance of the guide. Light entering the pipe at a large angle to the pipe axis, will undergo several reflections with corresponding light loss that depends to a great extent on the reflectance of the wall material (polished aluminium 85 %, silver coated plastics or aluminium 95 %, mirror-silver and aluminium enhanced with PVD process 98 %) (Travers, 1998). To attempt a minimum number of reflections, light must enter the guide as a near collimated axial beam.

Mirrored light pipes of small scale have been used quite successfully in domestic and commercial application for the enhancement of natural light in

rooms with poor illumination levels. The technology is also being applied in buildings with a large floor to facade ratio that need to be illuminated through the roof such as supermarkets, warehouses, etc. (Callow, 2003).

- **Solid core**

The major lighting applications of solid core systems are optical fibres. Fibre optics are light transport devices where light travels through the material by total internal reflection. They transport light from a remote point through thin flexible solid fibre with high efficiency and distribute it with standard light fixtures (Schade, 2002). Fibre optics comprise an inner core that acts as the light transport medium and outer cladding of lower refractive index that prevents leakage of light from the core. The process of total internal reflection in optic fibres is extremely efficient and light transport efficiency is a function of length, and not diameter as in the case of mirrored or prismatic transport. Light transmission through fibre optics depends specifically on the optical properties of the materials (Littlefair, 1990):

- The acceptance angle, which indicates the maximum beam spread of light that will successfully enter the flat end of a fibre, and where the most efficient fibres have lower acceptance angles.

$$\text{Critical angle}(\theta_c) = \sin^{-1} \left( 1 - \frac{(n_2)^2}{(n_1)^2} \right)^{\frac{1}{2}} \quad (2.4.1)$$

- The numerical aperture, which indicates the beam spread of light that the fibre will accept.

$$\text{Numerical aperture (N)} = \sqrt{n_1^2 - n_2^2} \quad (2.4.2)$$

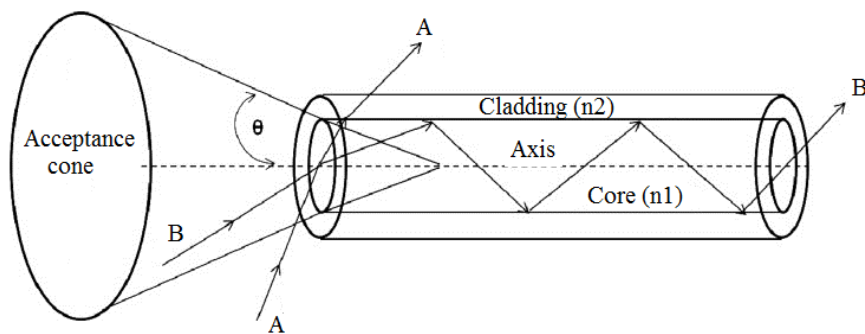


Figure 2.8: Light travels through fibre optic by total internal reflection

where  $n_1$  is the index of refraction of the core material, and  $n_2$  is the index of refraction of the outer cladding material.



### 2.4.3 Light distribution

The final component of light transport technology is the light distribution system that directs light from the guide to illuminate a space. Distribution of light requires extraction of light from the light guide and emission of light into the space. Depending on the light transport system and the scale of the device, light can be extracted at the end of the pipe in a continuous manner along the pipe (Rosemann and Kaase, 2005). Additionally, since transportation of light over long distances usually means the light is collimated, to achieve good illumination of all space, a device that distributes and spreads the light is required. The type and complexity of the emitter or luminaries will depend on the type of pipe used for light transportation (Edmonds, 1995).

Those transport devices that need highly collimated light also require complicated devices to distribute the light into space. For larger transport system such as mirrored light pipes, light distribution is easier, requiring only a diffuser at the end of the pipe. However, a prismatic pipe represents the best solution in terms of transport and distribution of light, since both actions are combined resulting in simpler solutions that will require less maintenance (Edmonds and Jardine, 1997).

## 2.5 Summary

The literature review was used to explore the daylighting systems that are being developed, studied or applied. There are two major groups of devices that seek to improve natural light in interiors; light guides and light transport devices.

Light transport devices improve illumination of the core space. Because light transport systems collect and transport natural light over long distances, they generally work with direct components of sunlight. The performance of all systems is reduced when the diffuse component of daylight is the only one present.

Hollow mirrored pipes that transport the light by multiple specular reflections are less complicated to build than other light transport systems and are currently relatively cheap and potentially have wide application in building design.

Table 2.2: Comparison of light transport system

Light transport medium	Collector	Principle of transmission	Efficiency	Cost	Major benefits	Major limitations
Lenses	Active	Converging refracting	28 %	Expensive	High transmittance (92 %)	Expensive and Difficult to maintain
Mirrored	Passive	Multiple specular reflection	70 %	Cheap	Available, cost effective and high reflectance	Not flexible and Bends reduce performance
Prismatic	Active	Total internal reflection	30 %	Expensive	Is both transport and distribution	Complicated collector, difficult integration into building and more costly
Fibre optics	Active	Total internal reflection	70 % (for 1 metre)	Expensive	Flexible	Complicated collector, low transmission and More costly

## Chapter 3

# The Light Pipe

### 3.1 Introduction

The term light pipe has long been used to refer to the family of non-image devices capable of transmitting light from either artificial or natural light sources inside buildings for illumination purpose. Light pipe family is divided into three groups (Yohannes, 2001); light pipes using artificial lighting as light source, light pipes using external daylight as light source and light pipes using both artificial light and external daylight as light sources. The light pipe group that uses external daylight as light source is also known as the solar light pipe since the ultimate source of daylight is the sun. As addressed in Introduction, the significance of utilizing and exploiting sunlight is emphasised in this study and the solar light pipe is the main concern of present research.

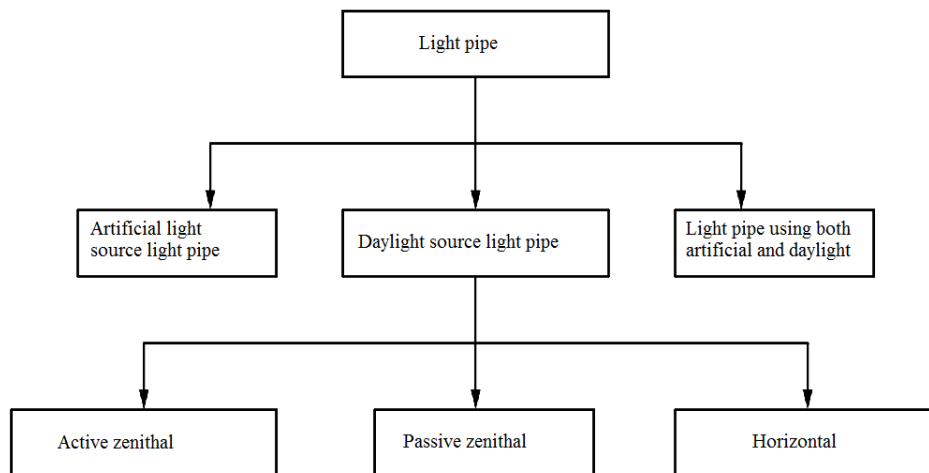


Figure 3.1: The light pipe family

Within the group of solar light pipe, further classification can be defined. The CIE (Commission International d'éclairage) has classified solar light pipe in three major groups defined by their collection methods (Riffat and Shao, 1999):

- Active zenithal (e.g. Heliostat systems)
- Passive zenithal (e.g. commercially available Solatube, Sunscope, Sun-pipe systems, etc.)
- Horizontal (e.g. anidolic ceilings)

The collector is usually located at roof level to gather light from the zenithal region of the sky and is either a mechanical device that actively focuses direct daylight (usually sunlight) or a passive device that accepts sunlight and skylight from part or the whole sky hemisphere.

## 3.2 The passive zenithal light pipe (PZLP)

Because of its main structure as a well-sealed tube, the light pipe has an added potential benefit in the reduction of excessive solar gain. Since piped, daylight emits off light only from light pipe diffuser, the output daylight is easier to control than other innovative daylighting systems. The flexible light pipe because of its structure enables designers put diffusers directly where illumination is needed so as to obtain a good interior distribution (Callow, 2003). By introducing redirected and diffused daylighting into the deep area of a room, glare from windows is reduced and daylighting is of a better uniformity. For skylight, designers attempt to admit more diffuse light by enlarging the facade area this always involves the danger of introducing undesirable sunlight into buildings. On the other hand, light pipes transmit sunlight and sky light by multi-reflect mechanisms, therefore the output daylight is much more uniform and diffused than that let in through a skylight. Another potential benefit of the solar light pipe is that it can be used in multi-storey buildings, while utilization of skylight is often limited to the perimeter zone of a building.

## 3.3 The structure of passive zenithal light pipes

The passive zenithal light pipe is the most commercially available light pipe system. Light pipes provided by different traders or manufacturers are to various extent slightly different from each other (Swift and Smith, 1995). The majority of commercially available light pipes consist of three main components associated with sealing components. The three main components are the daylight collector, the light pipe tube and the diffuser. The daylight collector is fitted at the top end of the light tube, usually on the roof. It acts

as a semi-lens to collect daylight and as a cap to prevent the ingress of water and dust. The diffuser usually fitted to the ceiling to allow the distribution of the daylight in the interior room space (Carter, 2002). The properties of main components of light pipe are described below.

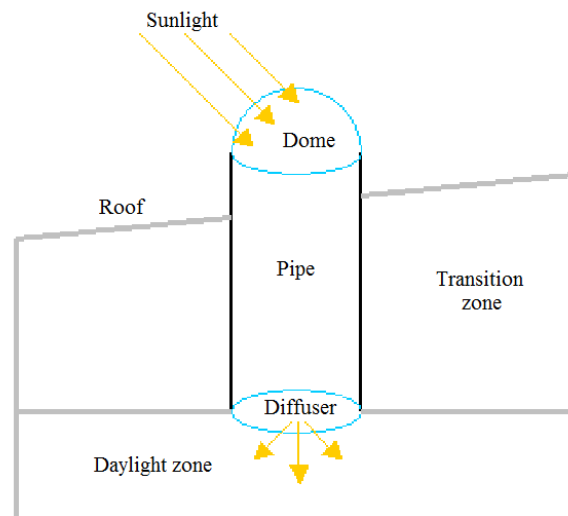


Figure 3.2: Passive zenithal light pipe components

### 3.3.1 The collector

The first component of the passive zenithal light pipe is the collector, the purpose of which is to collect daylight. The passive zenithal light pipe daylight collector is a dome-like shaped device, mounted on the roof, with the purpose of providing highly efficient light gathering. Two groups of dome collectors exist:

#### 1. Traditional dome collector

Traditional dome collectors can be manufactured from plastic or glass. Plastic domes are made from polycarbonate material, it is a very flexible plastic material which is not resistant to UV rays. Due this the sunlight will whiten or yellow the dome after a few years and thus reduce the light permeability by up to 50 % (Joel, 2000). People like the polycarbonate dome collector due to the fact that is easy to manufacture and cheap. The efficiency of the polycarbonate dome can be improved by producing it from plexiglass material. Plexiglass is a type of plastic material which has properties closer to that of glass. The main quality of the plexiglass dome is its excellent optical characteristic of collecting sunlight and its ability to channel it in the tube. It resists UV rays, temperature changes and moisture. Its disadvantage, is however a higher price.

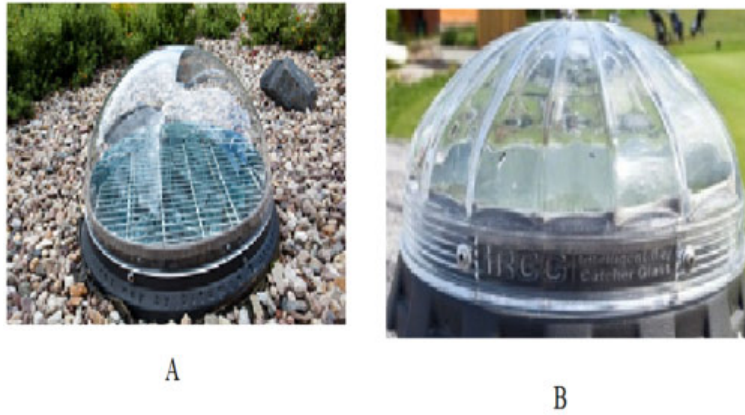


Figure 3.3: Traditional dome collectors. A: glass dome and B: plastic dome

## 2. Innovative dome collector

The traditional dome collectors don't have the ability to gather the low-angle sunlight of the morning and dusk hours also low-angle winter sunlight. For optimum performance of all time, traditional dome collectors can be fitted with with some technologies such as; lenses or deflectors.

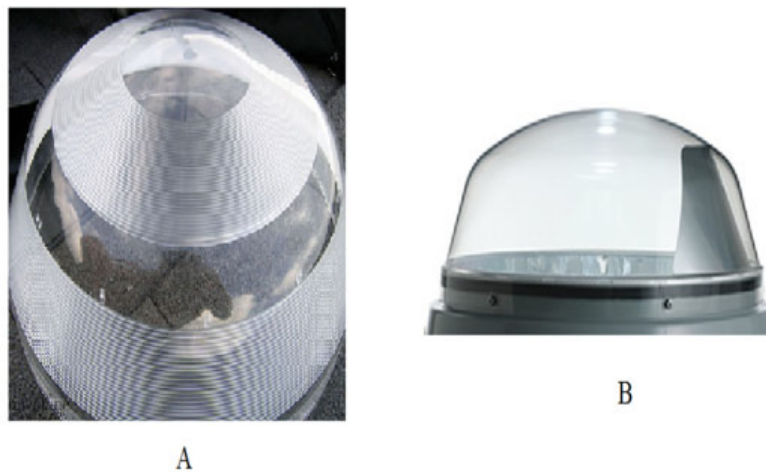


Figure 3.4: Innovative daylight collectors. A: ray-bender(Fresnel lens) dome, B: light tracker deflector dome

- Dome lens or Ray-bender dome technology: It consists of a series of Fresnel lenses positioned at critical locations inside the dome, that ensure that light is redirected into the tube at a steeper angle of incidence to minimize light loss.

- Light tracker deflector dome: It is particularly effective during the winter months, early morning and evening when the sun is low in the sky. As it is ideally positioned to reflect and redirect the low angle light into the tube at a steeper angle of incidence. Light that would otherwise have passed straight through the dome and been lost will be redirected.

The innovative dome collectors give consistent daylighting throughout the day, due to their ability to gather low-angle sunlight.

### 3.3.2 The tube

The tube is a light transmitting device in the light pipe. The reflectivity of the tube will determine how much light will get from the roof to the ceiling. The highest reflectivity tube delivers as much as 200 % more light than other tubes of the same diameter. The most efficient tubes are firm aluminium tubes with light-reflective layers some of which are silver produced by chemical vapour deposits in a vacuum. These tubes achieve a reflectivity, in the full colour spectrum, of 98 %, and in some colours 99.8 % (Hansen and Edmonds, 2003). They have shining flat surfaces with low sun-ray diffusion and the ability to transport the unchanged colours of sunlight over long distances without a loss of intensity. They are resistant to changes of temperature and moisture in the tube.

### 3.3.3 The diffuser

The diffuser has the form of a white polycarbonate dome mounted on the ceiling inside the room to be illuminated. The material of diffusers varies in transparency, so as to meet different needs for light distribution within the room. There are various kinds of diffusers that can be employed in light pipe systems (Baroncini C. and Zazzini, 2006); including dome opal, dome clear, recessed opal and recessed clear diffusers. The recessed diffusers are more effective in keeping out dust and preventing heat loss. Opal diffusers are of better diffusive property, and hence enable an even spread of daylight within the interior, while clear diffusers possess a better transparency and therefore can maximize the penetration of daylight. On occasion when soft and uniform daylighting is required, the former kind of diffuser has been widely used. For applications like the open space in deep-plan buildings and corridors where brightness becomes a priority, the latter kind of diffuser is more suitable. A new type of diffuser has been developed (Zhang X. and Kubie, 2002) the engineered diffuser with the ability to spread light with a specified divergence angle, control the spatial distribution of light and control the intensity of the diffuser light. A distinguished feature of the engineered diffuser compared to common diffusers, is that each of its scatter centres is individually designed and manufactured.

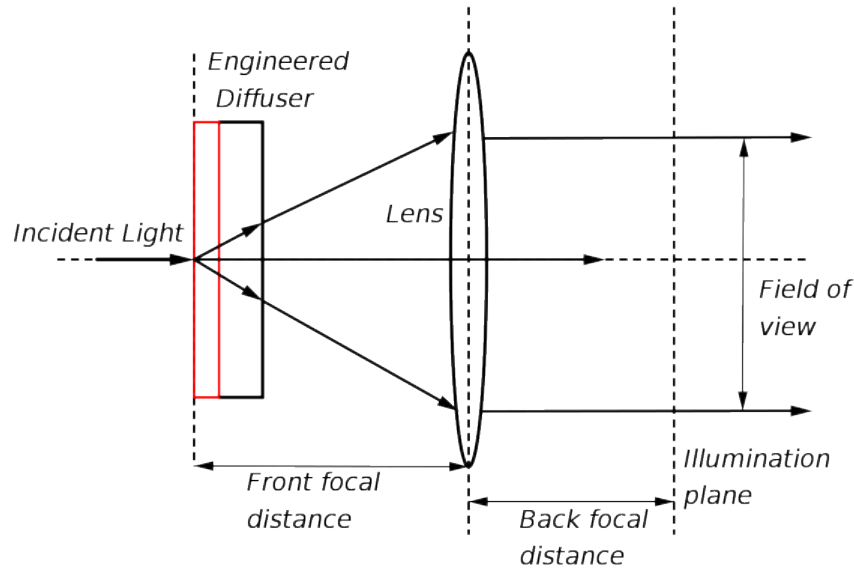


Figure 3.5: Illumination system with engineered diffuser

$$\text{Field of view} = \text{focal length} \times \tan(\text{diffuse angle})$$

### 3.4 The working mechanism of the passive zenithal light pipe

The design of passive solar light tubes allows them to collect, direct and diffuse light from the sun and sky. The dome-like shaped collector gathers direct and diffuse daylight illuminance, followed by multiple reflections of sunlight and skylight through the reflecting tube. Daylight then attains the inner surface of the light pipe diffuser where refraction followed by a light-scattering takes place before it is introduced within buildings. The complex light pipe's working mechanism consists of three aspects, namely the optical process, the external daylight environment and the design of the light pipe (Siriwat and Liu, 2000).

#### 3.4.1 The optical process

The first aspect is the complicated optical process that takes place within light tubes and diffusers. Initially daylight collected by the dome enters the light pipe, then a mixed multi-reflection of sunlight and sky diffuse illuminance occurs when daylight is transmitted through and diffused within the light tube. After that, a refraction phenomenon takes place in the light pipe diffuser when diffused sunlight and sky diffuse illuminance are further diffused and finally scattered into the interior space (Andersen, 2005).



### 3.4.2 The external daylight environment

The second aspect is the complexity of external daylight as the input to the light pipe system. The quantity and proportion of sunlight and sky diffuse radiation are not constant throughout the year. When sunlight is available, the change of the sun's position causes the variation of the incident angle at which the sun ray enters the light tube. This implies that the pattern according to which sunlight travels through the light tube is continuously changing when sunlight is available. When the sky is overcast or when clouds block the sun, skylight becomes the major external daylight source. The sky vault can be divided into small patches and each sky patch has its own position and brightness, so the transmission of the sky illuminance from each patch varies. Furthermore, the sky illuminance distribution is affected by the position of sun, the clarity of the sky, the position of random clouds and so on. Therefore, the process of sky-light entering the light tube and travelling within the tube is a highly dynamic. (Tregenza, 2004).

### 3.4.3 The design of light pipe

The third aspect is the conception of light pipes. Light pipes differ in their geometric configurations, including the length, the width and the number of bends incorporated in a light pipe system. The length and diameter of the light pipe are important in transmission of light. Larger diameter tubes produce more light than smaller diameter tubes also long light tubes have low light transmittance. Light tubes of small diameter are not effective due to material waste and light losses within the tube. For good performance the ratio length/diameter (L/D) of the tube should be small which will lead to few reflections.

Aspect ratio for both tubes:

$$a = \frac{L}{D} = \frac{4}{2} = 2$$

$$a' = \frac{L}{D'} = \frac{4}{3} = 1.75$$

$a' < a$ , there are three reflections in the first tube and two reflections in the second tube. That means the second tube will transmit more light than the first.

$$\text{Transmittance of tube : } T = \rho^N \quad (3.4.1)$$

where,

$N$  : number of reflections and  $\rho$  : reflectivity of material

The angle of incident also affects also performance of the light pipe. Light enters the pipe with a wide angle to the axis and undergoes numerous reflections which result in loss of light. The first tube with angle of incidence  $\theta$  transmits less light compare to the second with angle of incidence  $\beta$ .

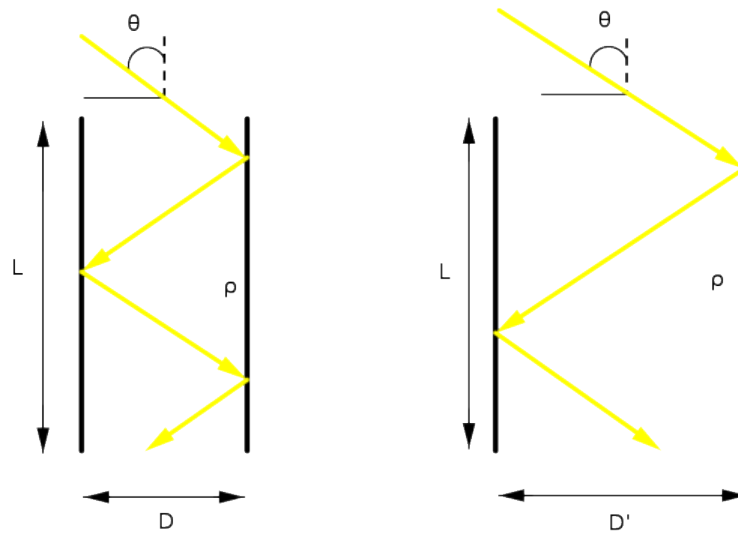


Figure 3.6: Sun's ray reflections in tubes of different diameters

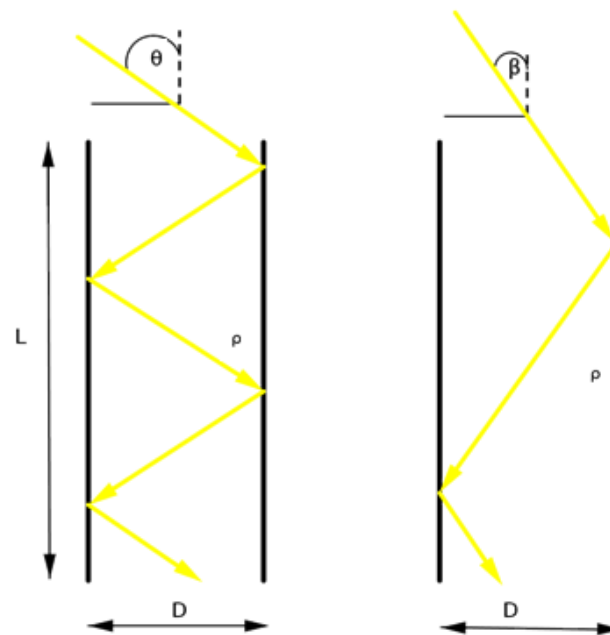


Figure 3.7: Sun's ray reflections in tubes of different angles of incidence

Transmittance equation of a collimated beam from Swift and Smith(1994)

is the following;

$$T = \frac{4}{\pi} \int_{s=0}^1 \frac{s^2}{\sqrt{1-s^2}} \rho^{\text{int}[a \tan \frac{\theta}{s}]} (1 - (1 - \rho)) (a \tan \frac{\theta}{s} - \text{int}[a \tan \frac{\theta}{s}]) ds \quad (3.4.2)$$

where

$a = \frac{L}{D}$  aspect ratio ,  $\rho =$  surface reflectivity and  $\theta =$  incident angle

Total light pipe beam transmittance

$$\tau_T(\theta) = \tau_{\text{dome}}(\theta) \tau_{\text{tube}}(\theta) \tau_{\text{diffuse}} \quad (3.4.3)$$

Light tubes applying different internal coating have different internal reflectance. For a given external environment and at a given point of time, light pipes of different configurations and having different internal coating materials produce different daylighting performance. For any given weather condition and sun's position, the cross area of a light pipe, affects the light pipe's external illuminance admittance. Since the daylight illuminance is transmitted by means of internal reflection within the light tube, and the reflectance although usually high is less than 1 (Zhang and Muneer, 2000a), a light pipe's overall transmittance is affected by the number of reflections required for a ray of light to descend the light tube and by the tube's reflectance. The higher the internal reflectance of the light tube, the higher the system's daylight transmittance. The lower the number of reflections required to descend the entire light tube the better the system's performance.

### 3.5 Transmission of sky diffuse light and sunlight within passive zenithal light pipes

The understanding of the complex process that sunlight and skylight travels through light pipes forms the basis on which a sophisticated performance model can be constructed. Previous research has been done on this subject (Lopez and Tovar, 1998). However, emphasis was only put on the explanation of the transmission of parallel light (or sunlight) within light pipe tubes. Sky diffuse light is the second most important component of daylight, but the contribution of this component to the daylighting performance of light pipes has rarely been studied.

The quantity and proportion of the two components of daylight vary with the changing of sky conditions. When the sky is clear, horizontal diffuse illuminance can be as high as 1/3 or more of horizontal global illuminance (Moon and Spencer, 1942) while when the sky is overcast horizontal diffuse illuminance can be equal to the global illuminance and when the sky is partly overcast,

the proportion of diffuse illuminance to global illuminance varies dynamically but can reach as high as 50 %. The transmission of sky diffuse illuminance can have important influence on the overall efficiency of light pipe systems. Study on the transmission of sky diffuse light within light pipes was carried out by BBRI (Belgian Building Research Institute) (Muneer, 1990). Measurement on the diffuse illuminance decrease in a 330 mm light pipe tube along the length of it was undertaken under overcast sky conditions. It was reported that diffuse illuminance transmitted by a light pipe had two components, namely the direct view part and the reflected part. It was shown that the direct view of sky decreased very quickly from 100 % to 1 % after 1 metre, while the reflected part decreased 29 % per metre. This implied that the physical processes of the transmissions of the two daylight components within light pipes were different (Zang, 2002).

The difference in mechanisms of transmitting sky diffuse and sunlight is mainly due to the different nature of sky diffuse and beam irradiance. Sky diffuse irradiance is from all angular directions within the  $2\pi$  solid angle range while sunlight is parallel with its direction dependent on the position of the sun (Shao, 1988). Therefore it is logical to suppose that the transmittances of sky diffuse and beam illuminance through a light pipe system can be different.

### 3.5.1 Transmission of sunlight

Numerous studies done on daylight pipes have shown that their transmission efficiency is a function of the number of reflections required for a ray of light to descend the pipe and of its reflectance. If sunlight of intensity  $I$  and elevation  $\alpha$  is incident on a light pipe tube of radius  $R$  and length  $L$  then the input power is (Seals and Michalsky, 1992)

$$P = \pi I R^2 \sin \alpha \quad (3.5.1)$$

At each reflection the light descends a distance  $2R \tan \alpha$  and the number of reflections is

$$N = \frac{L}{2R \tan \alpha} \quad (3.5.2)$$

However, the above calculation is only for a two-dimensional light pipe tube. In real applications, light pipes are three-dimensional. For a three-dimension light pipe tube, most light is not incident normally to the reflection surface of the tube and therefore will require more reflections to descend the tube. The number of reflections require to descend the light pipe is

$$N = \frac{L}{2R \cos i \tan \alpha} \quad (3.5.3)$$

If the reflectance of the reflecting surface is  $\rho$  then the transmission of a ray is  $\rho^N$ . The energy entering the aperture in the interval between  $x$  and  $x + \Delta x$

is proportional to  $\Delta x(R^2 - x^2)^{\frac{1}{2}}$ . Therefore the transmission of the light pipe tube for sunlight (defined as the ratio of output to input beam irradiance) can be obtained as (Muneer and Zhang, 2002):

$$T = \int_{x=0}^R \frac{(R^2 - x^2)^{\frac{1}{2}}}{R} \rho^{\frac{L}{2R \cos i \tan \theta}} dx \quad (3.5.4)$$

### 3.5.2 Transmission of sky diffuse

The transmission of sky diffuse light is more complex. However, by dividing the sky vault into a series of patches, the calculation can be carried out. Presume the radiance distribution is uniform and for a given sky patch, its azimuth angle is  $\Psi$  and altitude  $\alpha$ , then the horizontal diffuse illuminance ( $\Delta IL$ ) entering light pipe tube due to the sky patch can be obtained as (Naraghi, 1987):

$$\Delta IL = d\alpha d\Psi \sin \alpha \quad (3.5.5)$$

Where  $d\alpha$  and  $\Psi$  are span of the given sky patch in altitude tube and azimuth dimensions.

The total horizontal diffuse illuminance ( $E_{vd}$ ) input into light pipe tube can be obtained by either summing up the contributions of all relevant sky patches or by measurements. Say  $IL_n$ , is the horizontal diffuse illuminance entering light pipe tube due to a given sky patch, and  $T_n$  is the transmission of  $IL_n$  within the light pipe tube, then the total transmission of the sky diffuse illuminance ( $T_{\text{diffuse}}$ ) can be obtained as (Zang, 2002):

$$T_{\text{diffuse}} = \frac{\sum_{n=1}^{2I} IL_n T_n}{E_{vd}} \quad (3.5.6)$$

Above calculation of  $T_{\text{diffuse}}$  in Equation is based on the assumption that the sky luminance distribution is uniform, i.e. an isotropic model is used to provide the input illuminance value for light pipes. However, it is well known that the sky illuminance distribution is not uniform. Therefore, to calculate  $T_{\text{diffuse}}$  with a higher accuracy requires the application of zenith luminance models that can describe unisotropic sky luminance distributions (Zang, 2002).

## Chapter 4

# Experimental Analysis of the Passive Zenithal Light Pipe

In this section the focus is on test analysis of commercial PZLP composed of; plexiglass dome, mirrored tube and polycarbonate prismatic diffuser provided by Skylite Concept Company. The experiment was undertaken at the University of Stellenbosch between May and October 2013. A PZLP was installed on top of a sheet metal box of  $4\text{ m}^2$  surface. The test analysis of PZLP involves the installation of the light pipe in the sheet metal, collection, transmission and distribution efficiency test of dome, tube and diffuser respectively under sunlight (direct light) and skylight (diffuse light) conditions.

### 4.1 Experimental tests

#### 4.1.1 Tests equipment

The equipment used are mainly:

- **Commercial PZLP**

The commercial PZLP used consists of; a plexiglass dome of 250 mm diameter, a 400 mm long mirrored tube and polycarbonate-made prismatic diffuser, all provided by Skylite Concept Company.

- **Sheet metal box**

The box is made up of a galvanized smooth sheet with a square-shaped space of  $2\text{ m} \times 2\text{ m}$ . The PZLP is placed in the middle on the top of the box. There is no window in the box, a light pipe is the only daylight source active. The box is mounted on the roof of sun-lab, Department of Mechanical and Mechatronic Engineering.

- **Light meter/data logger instrument**

The light meter measures the illuminance (luminous flux incident on a surface) of an area. It displays and store lux in three ranges; 2,000, 20,000 and 100,000 lux from the supplied domed light sensor. It is able to store up to 3,000 readings. The logged data readings are stored in SD card in Excel format for easy transfer to a PC.



Figure 4.1: Experiment equipment: commercial PZLP, sheet metal box and light meter (data logger)

#### 4.1.2 Collection efficiency of the dome

The sun collector device for the PZLP is an hemispherical dome made of plexiglass material, with the purpose of channelling or steering as much light as possible downwardly through the tube. The amount of light channelled by the dome downward depends on the external daylight available, which consists of both sunlight and skylight. Throughout the year as well as during the course of each day the quantity and proportion of sunlight and skylight vary. When the external daylight is sunlight (input light to the light pipe) the angle of incident at which the sun rays enter the tube varies depending on sun's position. For the overcast sky or when the sun is blocked by clouds, the major external daylight source is sky. Determination of the amount of sky light entering the tube is a highly dynamic process due to the fact that sky illuminance is not uniform and is affected by the position of the sun, the clarity of the sky, the position of random clouds and so on.

The efficiency of the dome ( $\eta_d$ ) in collecting light was measured for direct light (sunlight) and diffuse light (skylight). Two light meters were placed on the top surface of the tube and on the roof at the surface of the dome for recording illuminance entering the tube and exterior illuminance at the level of the dome respectively. The efficiency  $\eta_{d1}$  under sunlight condition, was calculated as the ratio of direct horizontal illuminance  $E_s$  entering the tube to the exterior direct illuminance  $E_d$ . In the case of skylight  $\eta_{d2}$  was calculated as the ratio of diffuse horizontal illuminance  $E_{ob}$  entering the the tube to the exterior diffuse illuminance  $E_d$ .

$$\eta_{d1} = \frac{E_s}{E_d} \quad (4.1.1)$$

$$\eta_{d2} = \frac{E_{ob}}{E_d} \quad (4.1.2)$$

### 4.1.3 Tube transmission efficiency (TTE)

The interior of the PZLP tested is covered by highly reflective material (mirrored). The reflectance of the interior material is the primary parameter determining the TTE. The reflectance value ( $\rho$ ) provided by the manufacture is usually achieved by measures under ideal laboratory conditions and generally takes into account the reflectance at normal incidence of the light rays. Optical parameters of material's reflectance change over time due to its expose to external influences (e.g. pollution by atmospheric dust, etc.). In our case, manufacture provides the value of interior reflectance  $\rho \approx 90\%$  and transmits light away to the output device thanks to multiple internal specular reflections. The tube is 400 mm long and has diameter of 250 mm (the ratio  $L/D$  is 1.6) and it is straight without bends.

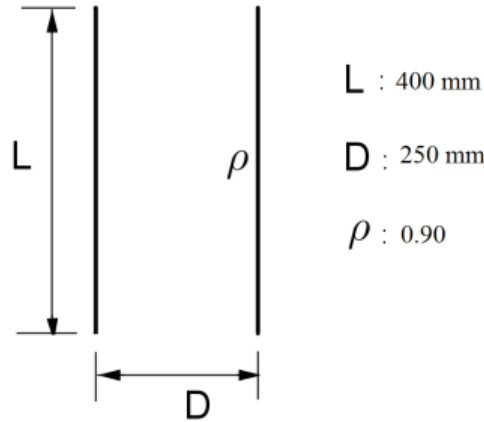


Figure 4.2: Dimensions and reflectance of the mirrored tube used



The ability of the tube to transmit daylight is the main measure used to evaluate its efficiency. Daylight transmission through light pipe tube depends on its length (L), diameter (D), reflectance of the internal surface and the sun's elevation angle. The efficiency of the light pipe is defined as being the ratio between luminous flux leaving the pipe and the luminous flux entering the pipe. As the climate conditions change the efficiency of the light tube also changes with them.

#### 4.1.3.1 Mathematical model

Many authors have developed mathematical models for the calculation of light transmission through mirrored light pipe. Those models have shown that transmittance of pipe depends on the number of reflections required for a ray to descent the pipe and its reflectance. In this section the transmittance ( $\eta_t$ ) of tube was calculated using the following two existing equations (developed by Swift and Smith 1995).

$$\eta_{t1} = \rho^{N_R} = \rho^{\frac{L \times \tan \beta}{D}} \quad (4.1.3)$$

$$\eta_{t2} = \frac{e^{\frac{L}{D} \times \tan \beta \times \ln \rho}}{1 - \frac{L}{D} \times \tan \beta \times \ln \rho} \quad (4.1.4)$$

$\eta_{t1}$  and  $\eta_{t2}$  are the transmission efficiencies of the light tube,  $\rho$  is the reflectance of the interior surface of the light tube,  $\beta$  is the angle of incident,  $N_R$  is number of reflections, L is the length of the tube and D is the diameter of the tube. The angle of incident  $\beta$  is calculated as follow:

$$\beta = 90^\circ - H_s \quad (4.1.5)$$

$H_s$  is the sun's elevation angle, this determines where in the sky the sun will be relative to the horizon on a given date and time in a given place.

#### 4.1.3.2 Scale model

For the scale model testing, the TTE was tested under two different sky conditions (direct sunlight and diffuse light). Two light meters were placed on the top of the tube and at the end of the tube for recording illuminance entering and leaving the light tube respectively. Under direct light condition,  $\eta_{t3}$  was calculated as the ratio of average internal illuminance  $E_p$  on the exit surface of the tube to the direct horizontal illuminance ( $E_s$ ) entering the light pipe. In the case of diffuse light  $\eta_{t4}$  was calculated as the ratio of average internal illuminance  $E_p$  on the exit surface of the tube to the diffuse horizontal illuminance ( $E_{ob}$ ) entering the light pipe.

$$\eta_{t3} = \frac{E_p}{E_s} \quad (4.1.6)$$

$$\eta_{t4} = \frac{E_p}{E_{ob}} \quad (4.1.7)$$

#### 4.1.4 Spatial light distribution analysis of diffuser

After being captured and redirected into the tube by the plexiglass dome, daylight (sunlight and skylight) is transmitted away through multiple reflections to the light output device called diffuser, and then it is distributed inside the room. The tube with reflective light sides in the same angle each reflection, which angle depends on the sun's elevation in the sky and thus varies throughout the day, limiting the efficiency and effectiveness of the light pipe in controlling the distribution of light in the building. Introducing a diffuser at the exit of the tube serves the purpose of distributing light uniformly in the interior.

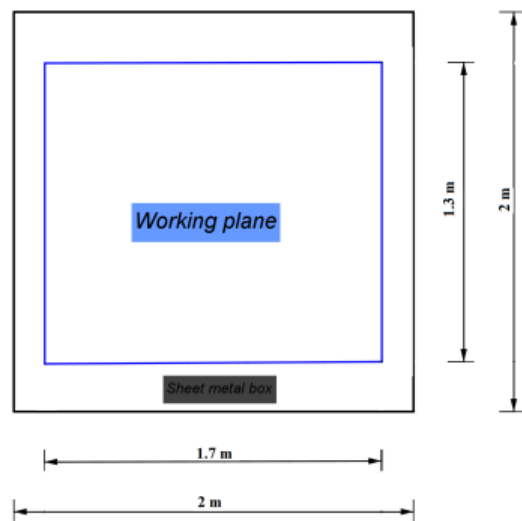


Figure 4.3: Work-plane in the sheet metal box

The diffuser considered is made of polycarbonate with prismatic geometry. Illuminance was measured in 30 positions (fig 4.11) on a horizontal work-plane, the work-plane was considered 2 m distant from the diffuser. During the experiment, the walls of the box were covered by a black sheet. In this way the influence on illuminance (at work-plane) of environment parameters such as wall reflections were limited.

## 4.2 Experimental results

### 4.2.1 Assessment results of dome collection efficiency

#### 4.2.1.1 Plexiglass dome

The daylight collection efficiency of the hemispherical plexiglass dome was tested by using a scale model. The efficiency  $\eta_d$  was considered as the ratio of direct horizontal illuminance entering the tube to the exterior direct illuminance, under sunlight condition and as the ratio of diffuse horizontal illuminance entering the tube to the exterior diffuse illuminance under skylight condition. Figure 4.4, illustrates the comparison of dome efficiency results under sunlight and skylight conditions from 6 a.m. to 7 p.m. in three months (June, July and August/2013).

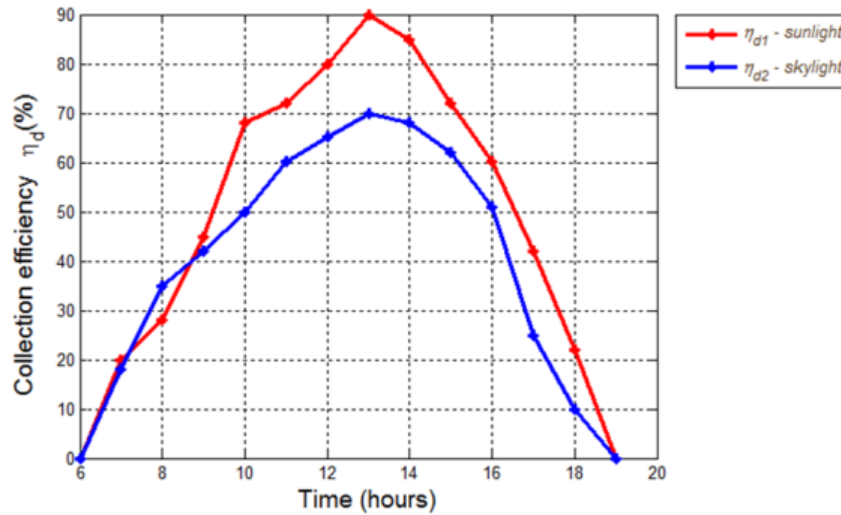


Figure 4.4: Comparison of dome collection efficiency under sunlight and skylight condition

From figure 4.4, it can be seen that  $\eta_{d1}$  (efficiency under sunlight) is higher at 1 p.m and decreases in the afternoon hours, and also that efficiency is very lower during the morning and at dusk due to the low-angle sunlight. Under skylight condition, sun is low in the sky and the light received by the dome is from the cloud and not direct from the sun, this results in lower efficiency during the whole day.

#### 4.2.1.2 Plexiglass dome with light deflector inside

The improvement of the lower efficiency during the morning and evening hours on sunlight and skylight conditions when the sun is low in the sky has also been tested by incorporating a deflector in plexiglass dome. The deflector is

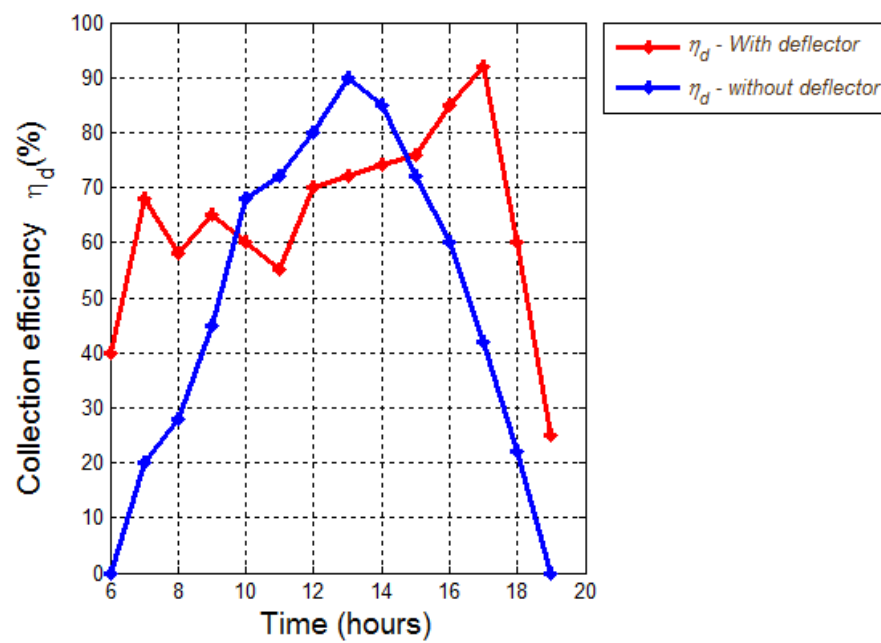


Figure 4.5: Comparison of dome collection efficiency with deflector and without deflector under sunlight

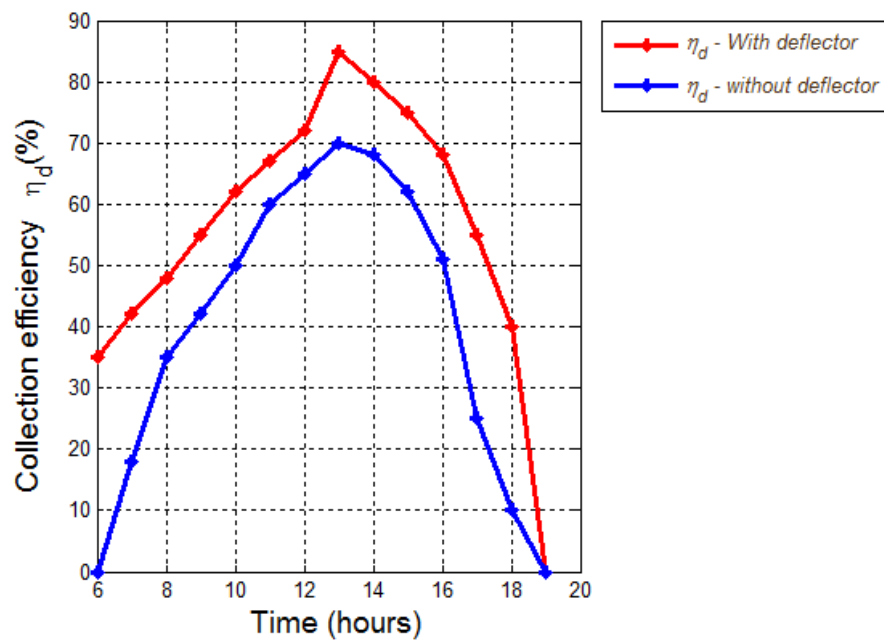


Figure 4.6: Comparison of dome collection efficiency with deflector and without deflector under skylight

positioned inside the dome and its purpose is to reflect and direct low angle light into the tube at a steeper angle of incidence which would be otherwise have passed straight through the dome and been lost. The results presented in Figure 4.5 and Figure 4.6 revealed that a light deflector in the dome can provide up to 6 % decrease in illuminance when there is significant direct light present. The results also revealed that under skylight it increases illuminance up to 30 %.

### 4.2.2 Assessment results of tube transmission efficiency

Assessment of tube transmission efficiency was done by using two models; a mathematical model and a scale model. The mathematical model was based on an equation developed by Smith and Swift ( equation 4.1.3) and an equation developed by CIE (equation 4.1.4) to obtain TTE under direct sunlight conditions. Results of calculated data according to the previous mathematical equations are shown in Figure 4.7 and 4.8.

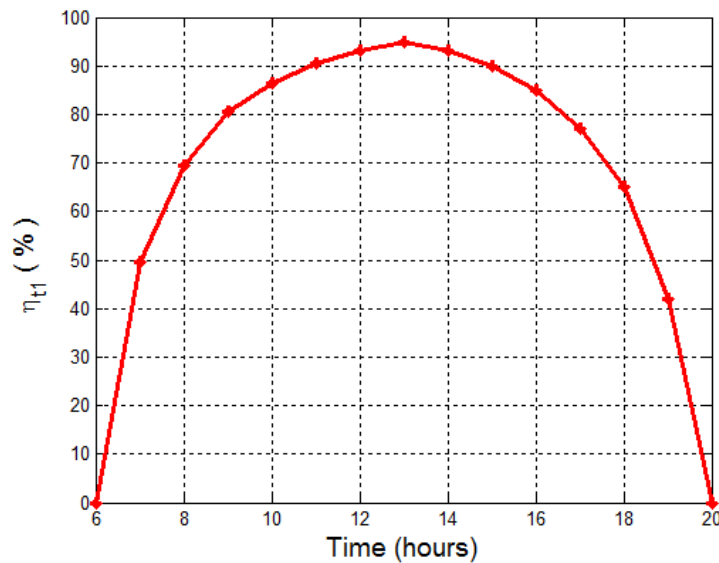


Figure 4.7: TTE results calculated according to equation 4.1.3 on sunlight days

For the scale model, TTE was calculated using data measured under direct sunlight and diffuse light conditions. The obtained results are plotted in Figure 4.9. TTE under direct sunlight conditions is higher between the hours of 11 a.m. and 2 p.m., with a higher sun elevation angle and lower in early morning and late afternoon hours. This change shows that the position of sun in the sky has big effect on the tube's efficiency. It is evident that TTE is

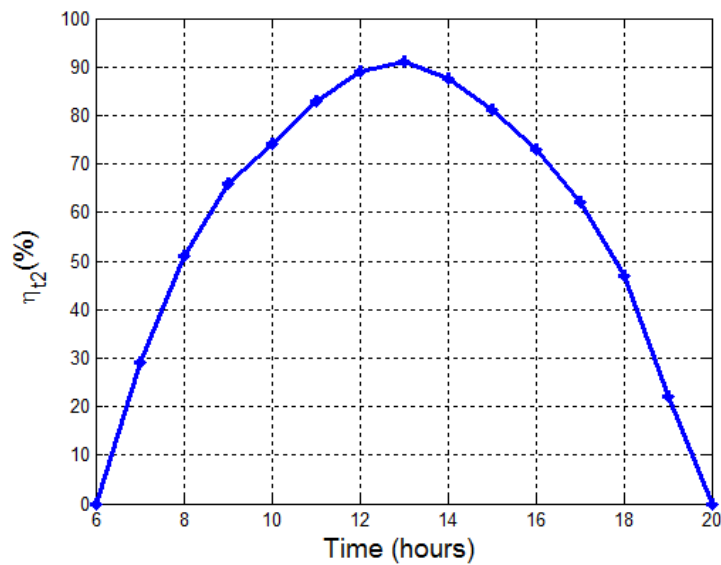


Figure 4.8: TTE results calculated according to equation 4.1.4 on sunlight days

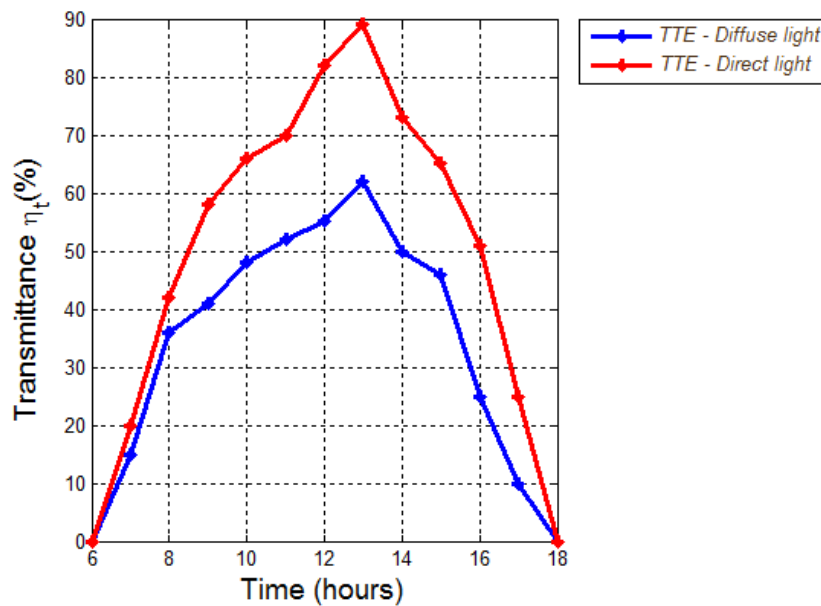


Figure 4.9: TTE measured under sunlight and skylight condition

higher under direct sunlight sky condition and lower under diffuse light condition. Under direct sunlight condition, results produced by equations 4.1.3 and 4.1.4 are overestimated in comparison with measured results. The average

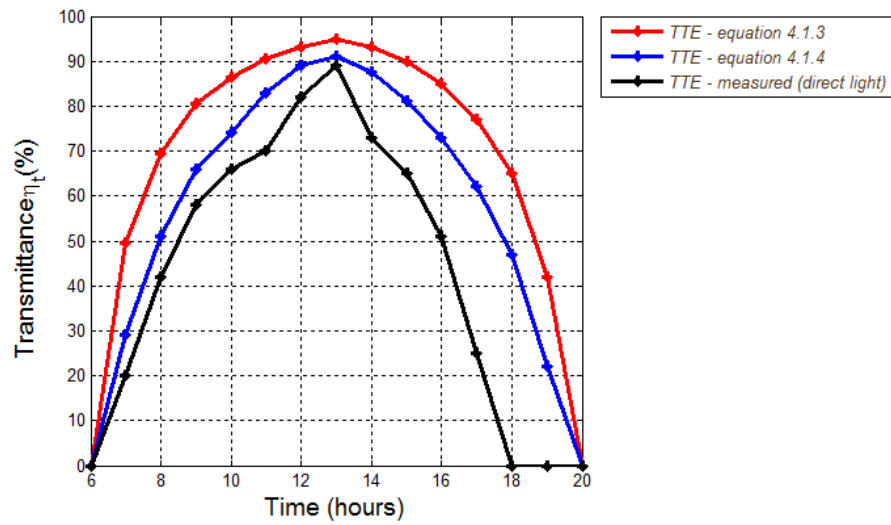


Figure 4.10: Comparison of TTE results calculated and measured under sun-light condition

deviation (final deviation ) between the results of the tube transmission efficiency achieved by measuring and the calculated results according to equation 4.1.3 is 11 % whereas a comparison of the same measured data with the data calculated according to equation 4.1.4 showed an average deviation of 5.5%. According to results achieved it can be said that, the equation 4.1.4 is more suitable than equation 4.1.3. But it is evident that theories based on constant inner reflectance of the tube are not suitable for the correct determination of TTE. Figure 4.10, illustrates the comparison of TTE results calculated and measured under direct sunlight.

In the case of TTE under diffuse light (overcast day), the measured results have not been compared to data calculated in equations 4.1.3 and 4.1.4 due to the fact that, results produced by those two equations depend on incident angle of sunlight which mainly depends on the sun's elevation angle. Illuminance distribution of the sky is affected by the position of sun, the clarity of the sky, the position of random clouds and so on. Consequently, the process of skylight entering the light tube and travelling within the tube is a highly dynamic process.

### 4.2.3 Light distribution assessment results

The light distribution on the horizontal work-plane has been assessed in two ways. The first way was when there was no diffuser at the exit of the tube, only a light tube controlling interior distribution. The second way was when a polycarbonate prismatic diffuser was applied to spread light through tube

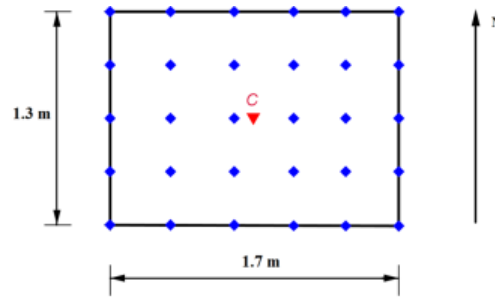


Figure 4.11: Measure positions

interior. Illuminance readings were taken in 30 positions on the work-plane as represented in Fig 4.11, under direct sunlight at 9h, 11h, 13h, 15h and 17h.

#### 4.2.3.1 Without diffuser

Interior illuminance distribution results, on the work-plane without use of diffuser are illustrated in Fig 4.12. It can be said that the tube with reflective light sides in the same angle each reflection, which angle depends on the sun's elevation in the sky and thus varies throughout the day, limiting the efficiency and effectiveness of the light pipe in controlling the distribution of light in the building in presence of direct sunlight. Illuminance distribution on the work-plane has been seen to be inconsistent especially during high sun's elevation hours also the light levels were very low (average of 45 lux from 9 a.m. to 5 p.m.).

#### 4.2.3.2 Diffuser

The results in Fig 4.13 show that the polycarbonate prismatic diffuser is able to provide a more uniform spatial light distribution under direct condition compared to tube distribution. But both, tube and diffuser produce very low light levels (an average of 45 lux and 178 lux respectively) on the work-plane compared to the illuminance intensity reached at the exit surface of the tube (25,000 lux).

## 4.3 Summary

The performance efficiency of PZLP was tested by means of the plexiglass dome, mirrored tube and polycarbonate prismatic diffuser. From results, it was seen that the plexiglass dome can collect up to 90 % of direct light (sunlight) and 70 % of diffuse light (skylight). As study on the improvement of dome efficiency for low sun elevation angles (skylight condition, morning and dusk hours) was done and results from many readings over fourteen hours, revealed that the light deflector incorporated in the plexiglass dome increased



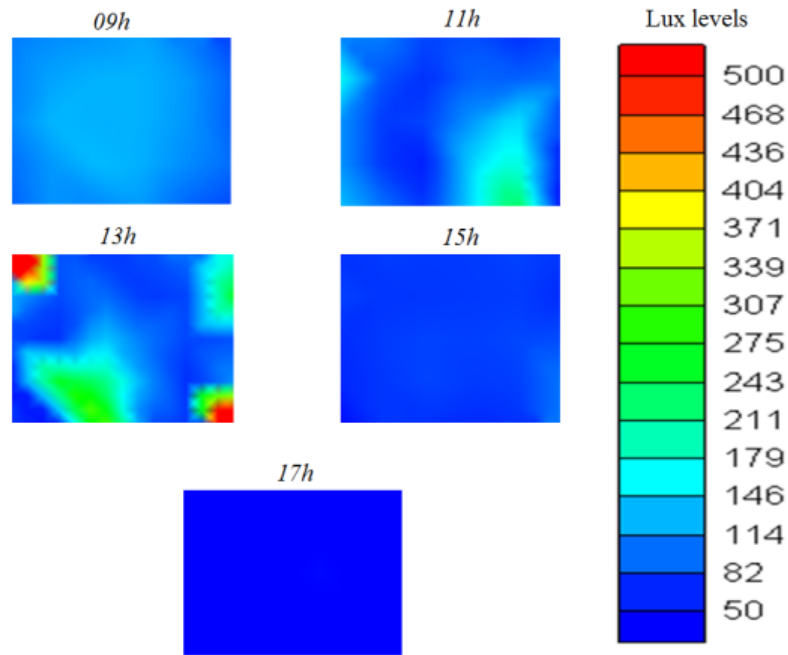


Figure 4.12: Tube interior light distribution

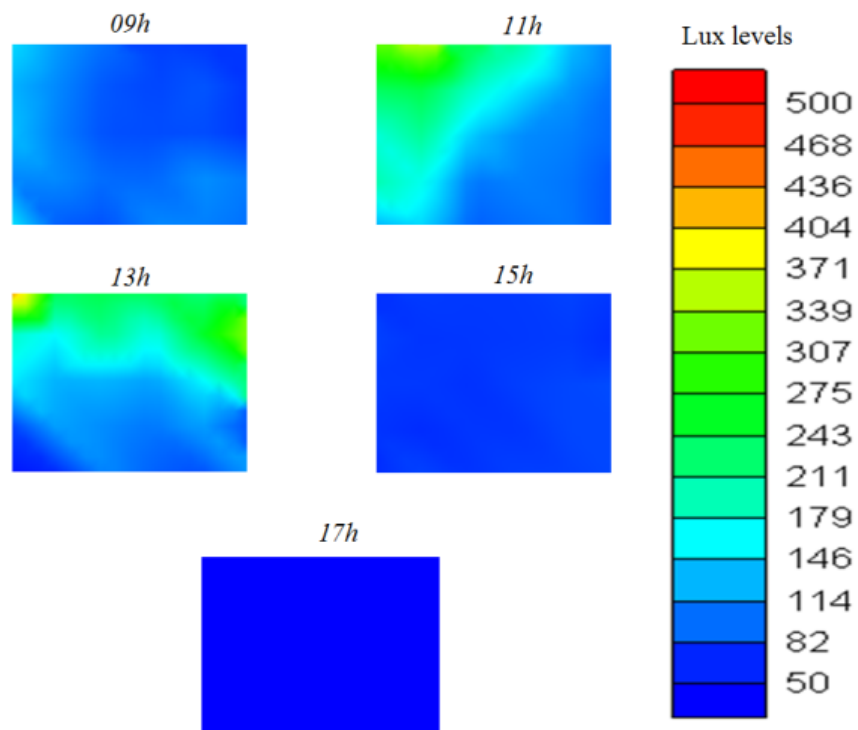


Figure 4.13: Diffuser interior light distribution

illuminance up to 30 % under skylight. From TTE results, it was seen that the mirrored pipe (of 1.6 ratio) transmits up to 90 % of direct light and 62 % of the diffuse light collected by the dome. Also from measurements, it was shown that TTE perform 31 % higher under direct sunlight condition than under diffuse light condition.

Analysis results for interior illuminance distribution through tube and polycarbonate diffuser, revealed that the light tube is not able to control distribution in the interior as it produces inconsistent distribution with very low light levels on the work-plane (average of 45 lux from 9h a.m. to 5 p.m.). With a diffuser a more uniform spatial light distribution was observed on the work-plane but the light level was very low (average of 178 lux from 9h a.m. to 5 p.m) compared to illuminance transmitted by the tube (25,000 lux).

## Chapter 5

# Design, Manufacture and Test of Light Collimator

The overall efficiency of PZLP at a given incident angle depends mainly on; the light capturing efficiency of the dome, light transmission efficiency of the tube and light output distribution efficiency. This means that low efficiency of these three parts (dome, tube and diffuser) leads to low performance of PZLP just as the PZLP's performance will increase if these components efficient is high.

$$\tau_{\text{overall}}\theta = \tau_{\text{dome}}\theta\tau_{\text{tube}}\theta\tau_{\text{diffuser}}\theta \quad (5.0.1)$$

The findings of tests on PZLP components (reported in the previous chapter) showed that, from dome to tube exit surface an average of 25,000 lux illuminance is available to be used in the interior of the building under direct sunlight condition. But an average of only 178 lux reached the work-plane through the diffuser, which may cause visual discomfort to the user of the plane. The present invention has been recognized to optimize the light transmission through the tube with uniform distribution.

### 5.1 Light collimator design

A light collimator is a non-imaging optical system which focuses on transferring light efficiently and controlling its distribution. Its design is based on what is called the edge-ray principle or sometimes called the string method. The concept behind the edge-ray method is that the extreme rays at the input aperture are also extreme rays at the output aperture. Rays in between the edge rays also strike the output aperture although the path they take may involve multiple reflections. The collimator profile that performs the mapping is a partial parabolic profile. The comparison of collimator design to imaging design is that in imaging designs the effort is often focussed in the centre of

the field, whereas in collimator design the efforts are focussed at the edge of the field.

### 5.1.1 Design assumption

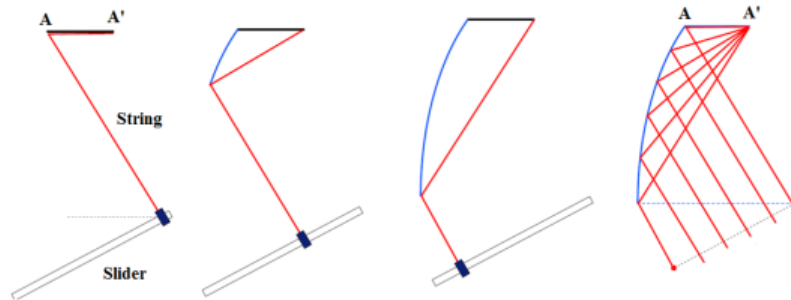


Figure 5.1: String method

Rays from the edge of the input aperture are sent to the edge of the output aperture after one reflection. This requirement determines the slope of the collimator at each point and the solution follows by continuity once a starting point has been chosen. The solution is continued until it reaches a termination point at which the collimator begins to intersect the edge ray that has already been used for determining another portion of the collimator.

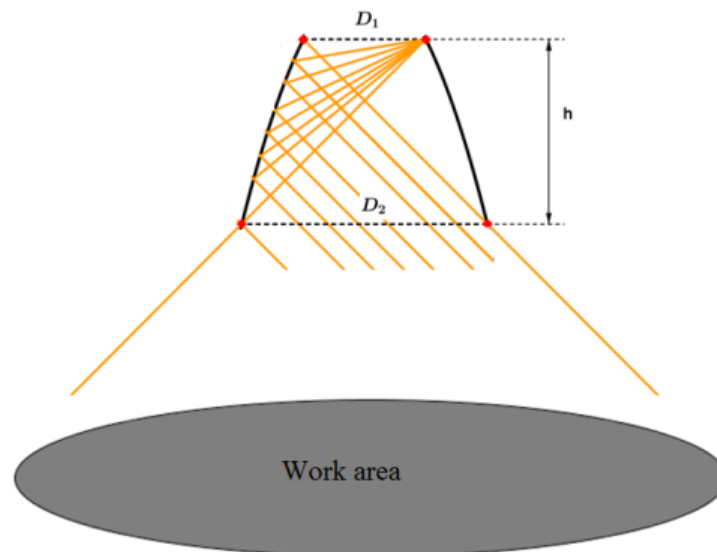


Figure 5.2: Collimator design assumption

### 5.1.2 Design consideration

When designing a light collimator it is necessary to determine the following parameters:

- Amount of light available at the exit surface of the tube

Sunlight after being captured by the dome undergoes multiple reflections before reaching the exit surface of the tube. The amount of light reaching the exit depends mainly on the sun's position. In the case of direct sunlight, the sun is visible which results in a very non-uniform luminance distribution while diffuse light entering and exit the pipe from many direction (isotropic) as it has been reflected by the cloud cover, results in a relatively smooth distribution of light from the tube.

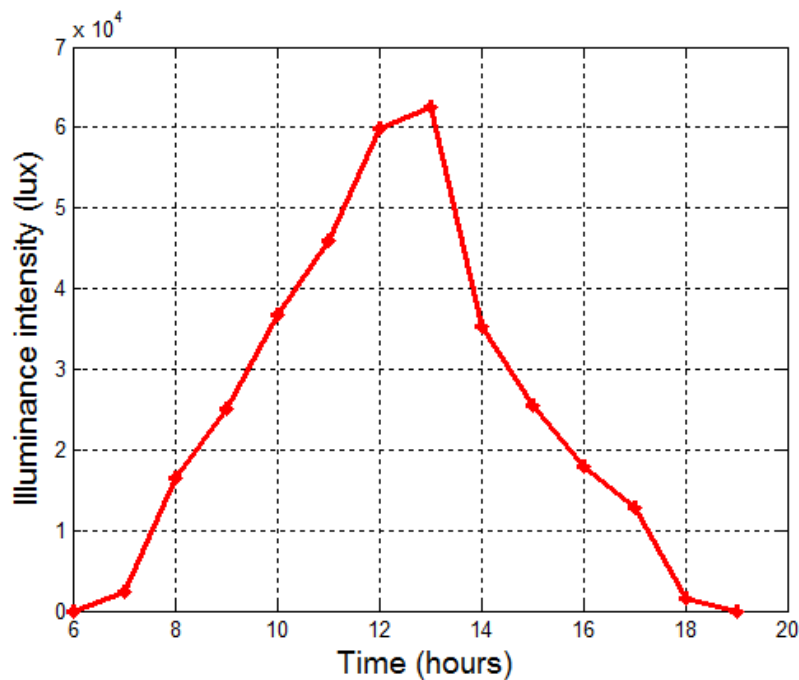


Figure 5.3: Illuminance intensity at the exit surface of the tube under direct sunlight condition

Due to this direct sunlight has been considered as the major condition for the design of the collimator. The illuminance intensity at the exit surface of the tube was varied from 0 lux in early morning hours, 62,500 lux at 13h and 25,000 lux in the afternoon hours as it is shown in Figure 5.3. The total average illuminance intensity considered is 25,000 lux at the exit of the light pipe tube.

- Area to be illuminated and illuminance required

The most important factor in system design is to assess what the application is trying to accomplish. The aim here is to illuminate a work area of  $2.21 \text{ m}^2$ . The collimator will be required to spread 500 lux at horizontal work area considered to be 1700 mm distant from it.

### 5.1.3 Manufacturing

The manufacturing of collimator was done by using laser cutting machine, hot wire foam cutting table and hand heater machine. These devices are the property of Cape Craft Design Institute (CCDI). The laser cut machine was used to print out the diameters (top and bottom ) drawn in open-office software to the card board. The hot wire foam cutting table was used as well as a hot wire to cut shapes and create collimator form from foam.



Figure 5.4: Laser cut machine, hot wire foam cutting table and shaped foam

The manufacturing of the collimator was done in three stages:

- Printing diameters ( $D_1$  and  $D_2$ ) on cardboard by using laser cutting machine,
- Cutting foam material in half of collimator profile with  $D_1$  and  $D_2$  sizes using hot wire foam cutting table machine,
- Heating a polystyrene sheet with the aid of a hand heater machine over foam collimator created a shape so as to get the final collimator made from polystyrene material.

## 5.2 Light collimator test analysis and results

After being designed and manufactured, the light collimator made from polystyrene material and with an interior lined with reflective film was tested. It was mounted at the exit of the tube, and its performance was measured on a horizontal work-plane considered to be 1700 mm distant from it. For optimum



Figure 5.5: Collimator made of polystyrene

performance, interior walls of the box were covered by black sheets, in this way the influence on illuminance (at work-plane) of environment parameters such as wall reflections was limited. The readings were taken in 30 positions (Fig 4.11) under direct sunlight. The collimator interior reflective materials tested are of three types; metallized weather-able acrylic film (3M solar mirror film 1100), cooking aluminium foil with a smooth surface and cooking aluminium foil with a rough surface.

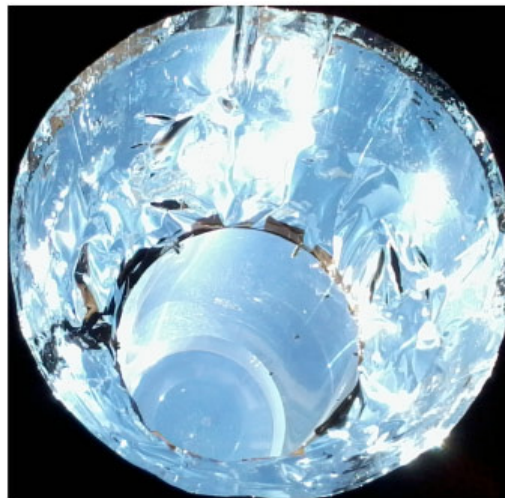


Figure 5.6: Collimator lined with 3M mirrored film and mounted on the tube

### 5.2.1 Test results

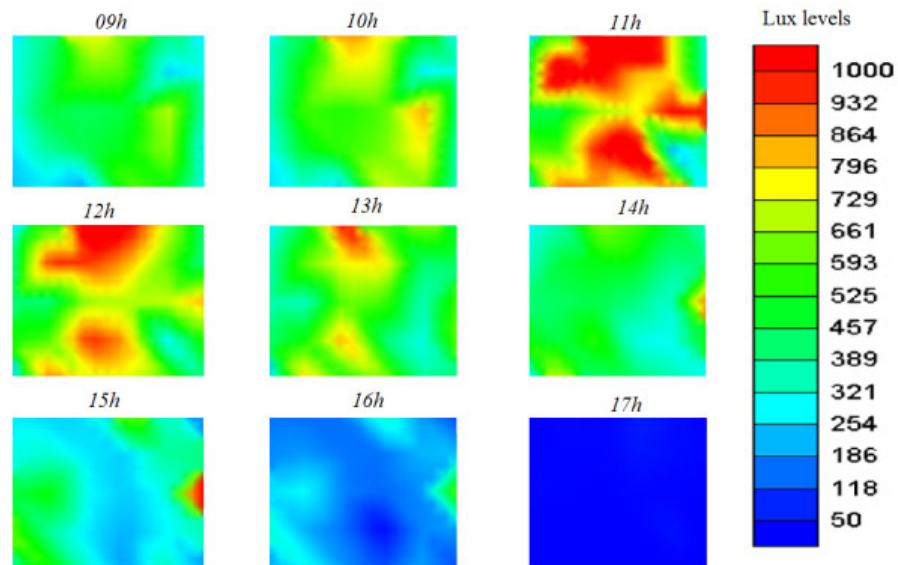


Figure 5.7: Light distribution of collimator lined with 3M solar film

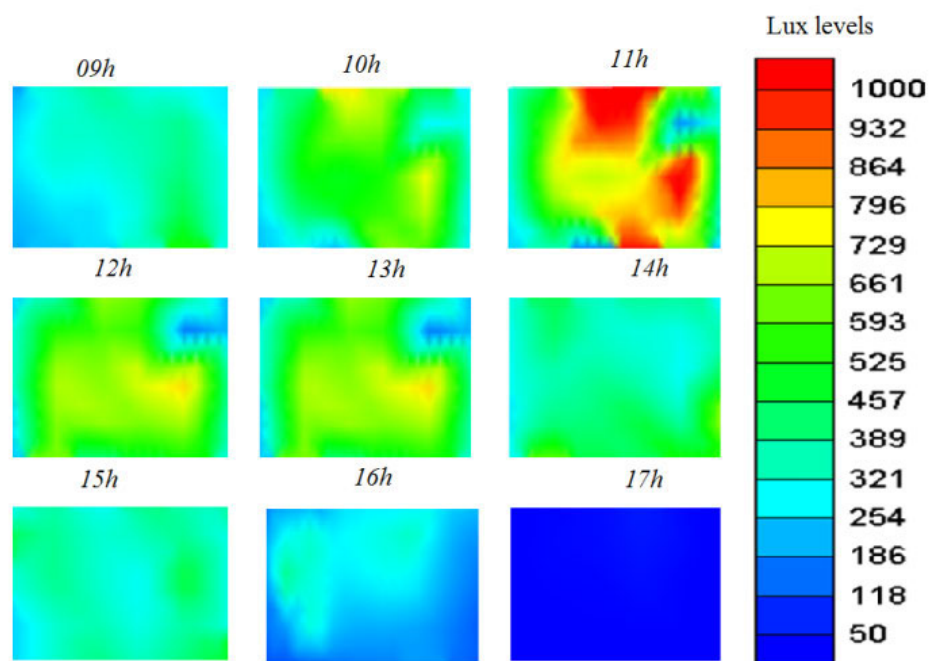


Figure 5.8: Light distribution of collimator lined with cooking aluminium foil with a smooth surface



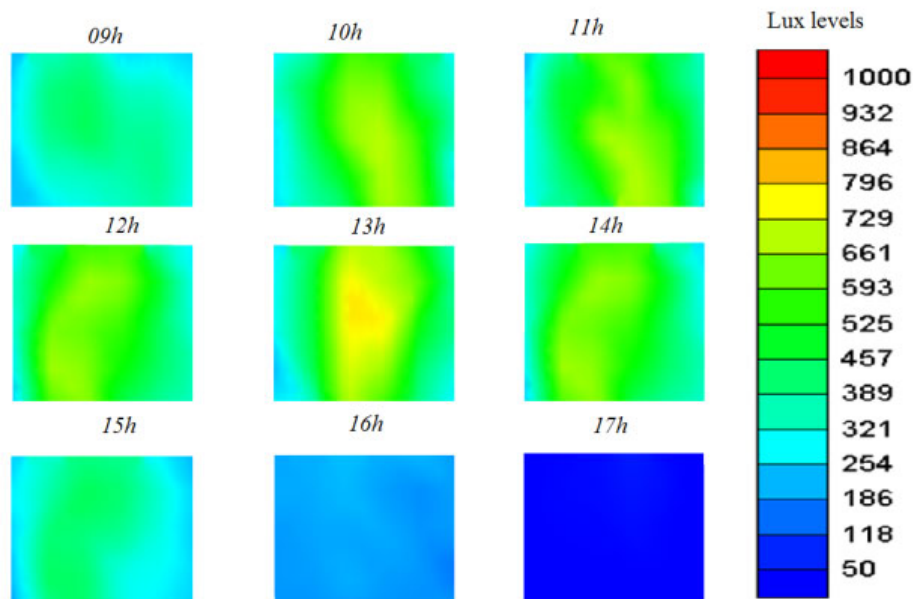


Figure 5.9: Light distribution collimator lined with cooking aluminium with a rough surface

### 5.2.2 Test analysis

Figures 5.7, 5.8 and 5.9 illustrate the results of light distribution of a 3M mirror film, cooking aluminium foil (smooth surface) and cooking aluminium foil (rough surface), measured on the 4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> October 2013, from 9 a.m. to 5 p.m. (i.e nine hours) on sunny days when the exterior illuminance varied between 45,000 lux and 96,000 lux. From the results, it can be seen that the direct light that is received by light pipe seriously affected the distribution observed on the work plane. The position of the sun obviously affected the angle that light entered the pipe and so affected the path that the light travelled through the pipe. Results of the collimator lined with 3M mirror film and cooking aluminium foil with a smooth surface showed that the distribution on the work-plane was not uniform and also that a ring pattern was observed especially at the 11h, 12h and 13h, when sun's elevation angle is high which may cause visual discomfort. It can also be seen in Figures 5.7 and 5.8 that direct sunlight produces a high light level at positions on the side and that the positions in the middle received less light despite being closer to the collimator. On the other hand results of cooking aluminium foil with a rough surface revealed uniform distribution on the work-plane and that positions in the middle (closer to the collimator) experienced a higher light level than positions on the sides.

Table 5.1: Lux levels on work-plane

Time (hour)	3M film	Al. smooth surface	Al. rough surface
	Lux	Lux	Lux
9	420	313	306
10	510	449	380
11	532	429	400
12	589	478	450
13	680	584	500
14	508	420	396
15	464	352	330
16	280	220	200

### 5.2.2.1 Comparison of smooth and rough surface reflective materials

- Reflectivity

Both surfaces, smooth (3M mirror film and cooking aluminium smooth film) and rough aluminium foil are reflective materials. 3M mirror film is a silver metallized weather-able acyclic film, it has a solar weighted total hemispherical reflectance of 94 % (manufacture reflectance) at air mass. Aluminium foil has a reflectivity of 87 % for smooth surface and a reflectance efficiency of 68 % (measured reflectance) for rough surface.

- Reflection principle

Both surface films were chosen due to their high reflectivity which allows sun rays which fall on them to be reflected. Sunlight may be reflected in two different ways depending on material surface they hit. Those reflections are specular and diffuse reflections. Specular reflection occurs when sunlight reflects off a smooth surface while diffuse reflection occurs when sunlight reflects off a rough surface. Figure 5.10 illustrates the smooth and rough surface reflection principle.

Sunlight is thought of as a bundle of individual light rays which are travelling parallel to each other. Each individual light ray of the bundle obeys the law of reflection. If a bundle of light rays is incident upon a mirror film surface or cooking aluminium foil smooth surface, the light rays reflect and remain concentrated in a bundle upon leaving the collimator. On the other hand the roughness of aluminium foil, means that each individual ray meets a surface which has different orientation. Subsequently, when the individual rays reflects off the rough aluminium foil according to the law of reflection they scatter in different directions. The result is that the rays of light are incident upon the rough aluminium foil in a concentrated bundle and are diffused upon reflection.

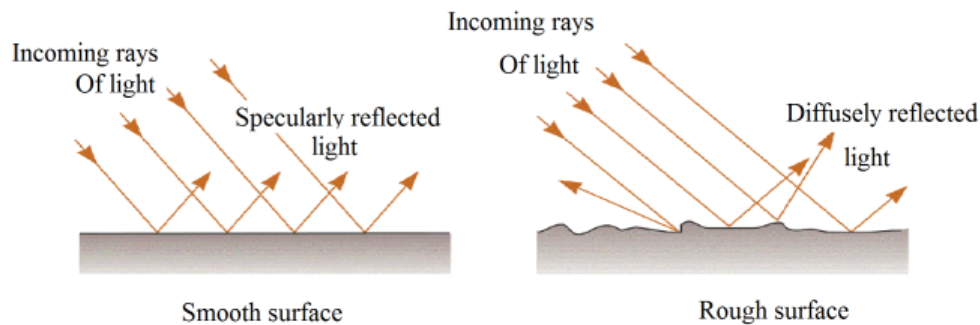


Figure 5.10: Sun rays reflections on smooth and rough surfaces

- Impact of specular and diffuse reflections on work-plane light distribution

The sun rays which leave the collimator lined with smooth surface film are concentrated and this results in annoying glare or some broken ring pattern distributions on the work plane, when the sun is at a high elevation angle while sun rays that leave collimator lined with a rough surface film are scattered in different directions (isotropic), this results in a relatively smooth distribution of light on the work plane.

## 5.3 Improved light collimator

### 5.3.1 Design

The improved collimator design was made after the analysis of results of the first collimator. There are three aspects that were improved:

- Interior lining reflective material

Based on their characteristic reflective materials are placed in three categories; specular, spread and diffuse materials. The specular materials such as mirror, optical coated glass, etc. provide directional control of light and brightness at specific viewing angles and they are recommended for special decorative lighting effects. The spread materials, generally diffuse reflection with a high specular surface reflection. And diffuse materials, produce uniform surface brightness at all viewing angles, they are a good luminous form. Table 5.2 shows the typical reflectance of common reflective materials.

The first design of the collimator was made based on aluminium foil (smooth surface) and it was seen in the results that its light distribution on the work-plane was inconsistent. For the improved collimator a white paint reflective

inner surface with an average of 84 % reflectance efficiency was considered for design due to its light distribution characteristics (diffuse reflection).

Table 5.2: Reflecting materials and their distribution

Distribution	Material	Reflectance
Specular reflection	Mirrored and coated glass	80 - 99 %
	Metallized and coated plastic	75 - 97 %
	Polished aluminium	60 - 70 %
	Chromium	60 - 65 %
	Stainless steel	55 - 65 %
Spread	Processed aluminium	70 - 80 %
	Etched aluminium	70 - 85 %
	Brushed aluminium	65- 75 %
	Aluminium paint	60 - 65 %
Diffuse reflection	White plaster	87 - 92 %
	White matte film or paint	80 - 88 %
	White terra-cotta	65 - 80 %

- Illuminance on work plane

Illuminance of 500 lux was considered for the first collimator design. The amount of light needed in a certain rooms depends on the nature of the task which will be carried out. The tasks to be performed here are reading and writing (refer to the Table 1.1) the illuminance required by SABS for reading and writing is between 200 lux and 500 lux. An average of 350 lux was considered for the improved collimator design.

- Shape errors

Because the first collimator was made manually some errors occurred especially in collimator profile. The improved collimator was made industrially in PRESPIN, in order to avoid those errors.

### 5.3.1.1 Design consideration

1. Illuminance available: 25,000 lux (average sunlight)
2. Area to be illuminated:  $2.21 \text{ m}^2$
3. Illuminance required: 350 lux
4. Interior lined material: white matte film (84 %)

Figure 5.11, represents the improved collimator made from brushed aluminium. Its design drawing representing dimensions is presented in Figure B.2 (in Appendix B).



Figure 5.11: Brushed aluminium collimator

### 5.3.2 Test analysis and results

The improved collimator made from brushed aluminium was tested for its light distribution performance. The interior lined reflective materials tested are:

- Brushed aluminium surface
- 3M mirror film
- Cooking Aluminium foil with a smooth surface
- Cooking Aluminium foil with a rough surface
- White matt film

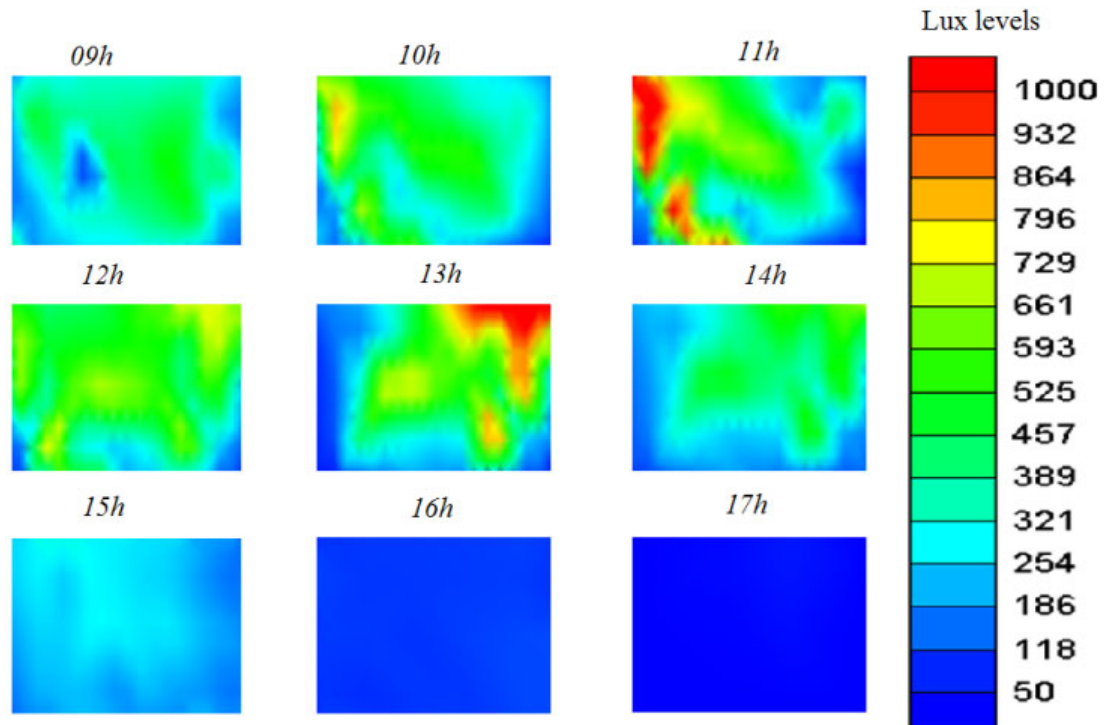


Figure 5.12: Brushed aluminium surface light distribution

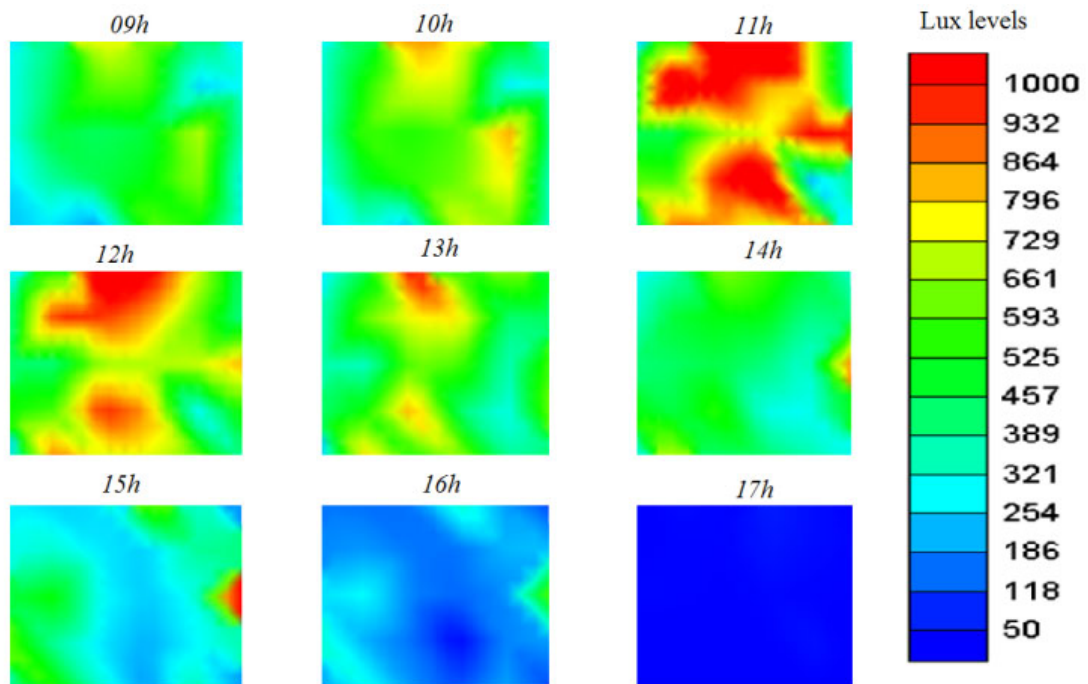


Figure 5.13: 3M mirror film surface light distribution

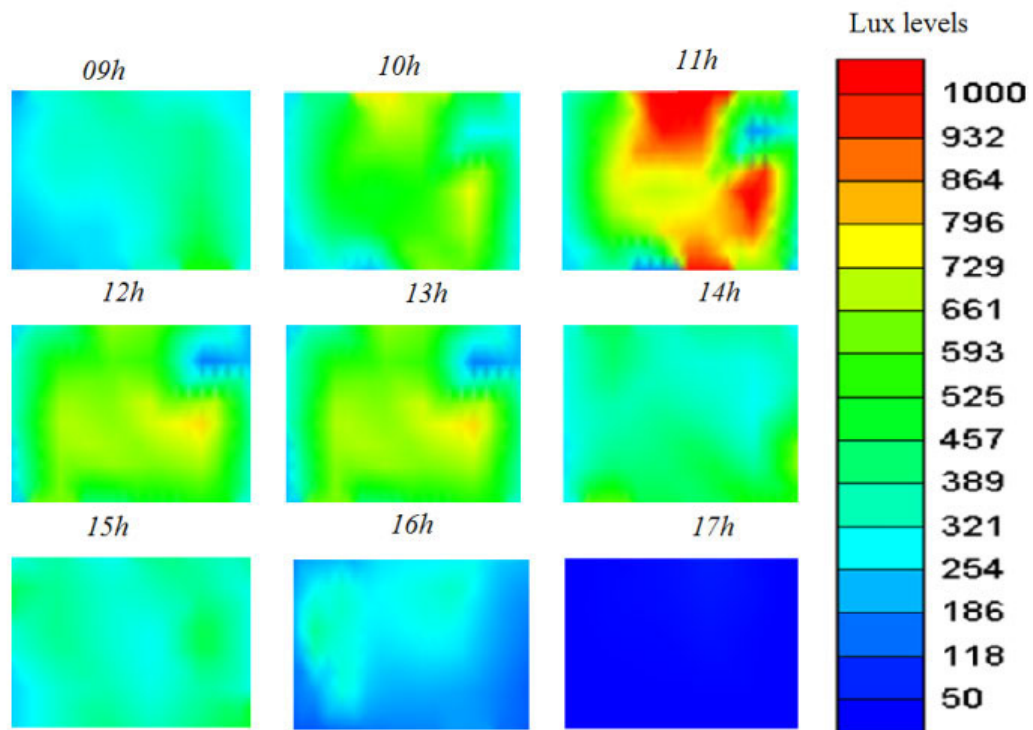


Figure 5.14: Cooking aluminium foil smooth surface film light distribution

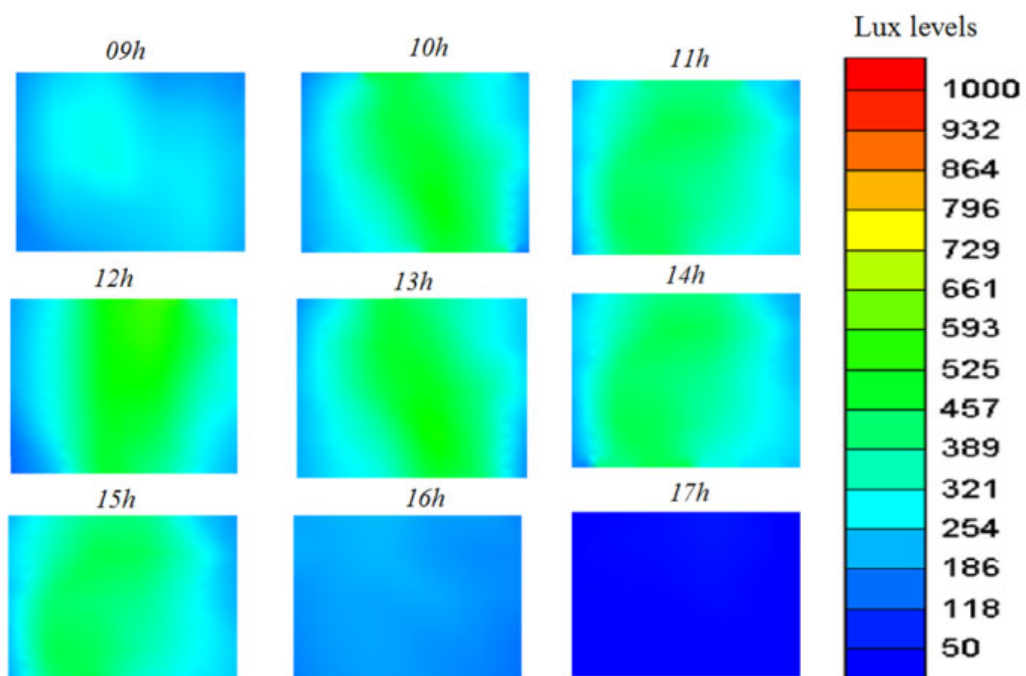


Figure 5.15: Cooking aluminium foil rough surface film light distribution



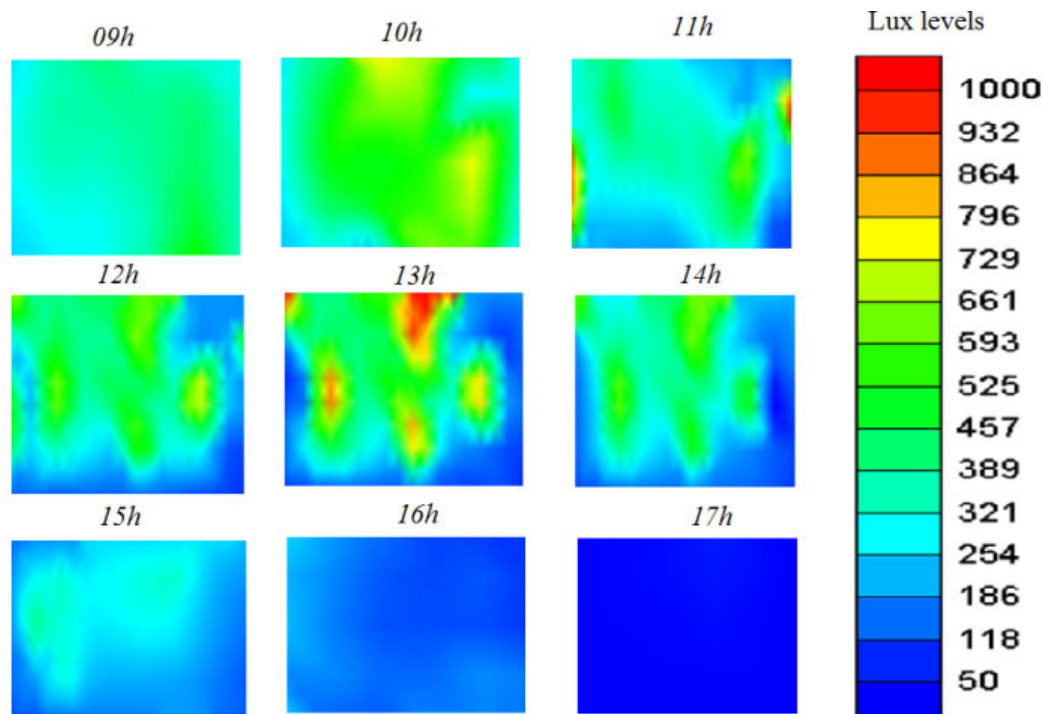


Figure 5.16: White matt film surface light distribution

Table 5.3: Comparison table of different lined interior reflective surfaces

Performance	3M mirror film	Cooking alum. foil(smooth surface)	Cooking alum. foil(rough surface)	Brushed alum.	White matt film
Material reflection	Specular	Diffuse	Diffuse	Spread	Diffuse
Light Levels(9h-17h)	519 lux	405 lux	370 lux	324 lux	300 lux
Illuminance distribution	Inconsistent	Inconsistent	Uniform	Inconsistent	Inconsistent
Manufacture reflectance	94 %	87 %	87 %	70 %	80 %
Measured reflectance	83 %	78 %	68 %	65 %	60 %

The main aim of designing the light collimator was to improve the efficiency of the passive light pipe from 178 lux spread by polycarbonate prismatic diffuser to an average of 350 lux required in the classroom. The light collimator made from brushed aluminium was tested with different lined interior reflective surfaces (Brushed aluminium, 3M mirror film, cooking aluminium foil film



smooth surface, cooking aluminium film rough surface and white matt film). Results showed that of the five reflective surfaces tested, only re-used cooking aluminium foil (of rough surface) results in a uniform spatial light distribution with an average light level of 370 lux from 9h00 to 17h00.

## 5.4 Summary

Through the design and manufacture of the light collimator, illuminance in the classroom has been improved from 178 lux distributed by commercial diffuser to 370 lux distributed by the light collimator. The problem however was the presence of glare patches of the order of 1000 lux. A range of reflector materials were tested but yielded similar disappointing results. Finally a breakthrough emerged when a novel reflector material using rough re-used aluminium cooking foil was discovered that totally eliminated these patches.

# Chapter 6

## Field Test Site

### 6.1 Introduction

In this chapter a classroom case study used in this project to assess the performance of the light pipe and collimator is described. This assessment has been done by scale model testing. The case study is the design proposal for the main classroom (renewable energy classroom) at the Sustainability Institute at Lynedoch. It details the research undertaken in assessing the light pipe and collimator as one of daylighting solutions for this classroom. The objective was to assess the performance of the passive light pipe in delivering natural illumination, and to determine the benefits and limitations of this technology.

### 6.2 Field test site description

The Sustainability Institute is an international living and learning centre located outside the South African university town of Stellenbosch. It is an inspiring example of what ecological education can look like. The institute provides a space for people to explore approaching towards creating a more equitable society that lives in a way that sustains rather than destroys the eco-system within which all society is embedded.

#### 6.2.1 Design parameters

The general parameters of the classroom tested include:

- Area: 180  $m^2$
- Height: 2.5 m
- Length: 18 m
- Width: 10 m

The average number of students who may occupy the room is 45 students. One of the ways to make significant savings in the power demanded for electric lighting and air conditioning in the classroom is to use a daylighting system. Consequently, the major issue with natural illumination for this classroom is how to reduce glare entering the space from windows and to better distribute daylight in the interior (Fig 2.3).

### 6.2.2 Daylight availability

Availability of sun in different seasons and possible shadows at the site were assessed by using the SunEye-210 tool. SunEye is a measurement tool for site assessment. It is a hand-held electronic tool that assesses the available solar energy by day, month, and year with the press of a button by measuring the shading patterns of a particular site. Assessment results of solar access, elevation and azimuth angle of the sun, are presented in figures C.4 and C.5 in Appendix C.



Figure 6.1: SunEye-210 tool

## 6.3 Tested daylighting system

The daylighting system tested in the classroom at Lynedoch is composed of a plexiglass dome ( $\phi$  250 mm), a mirrored tube ( $L=$  1300 mm) and a collimator ( $\phi$  361 mm) for sunlight collection, transmission and distribution respectively. It is installed in the middle of the classroom.

### 6.3.1 Sunlight collection

A plexiglass dome collector with a light and sun deflector (a small reflective panel, curved and inclined so as to fit snugly around the base of the dome to reflect small light angles down the pipe) is fitted at the top of the light pipe on the roof for sunlight collection.

### 6.3.2 Light transmission

Daylight collected travels down the reflective tube through multiple specular reflections. The transmission in the tube depends on the pipe material of 95 % of transmittance.

### 6.3.3 Light distribution

In order to distribute daylight more widely and uniformly, the interior of the light collimator (Figure 5.11) was lined with cooking aluminium foil (rough surface) and installed at the end of light tube at ceiling level.



Solar dome collector on the roof



Collimator light distribution

Figure 6.2: Sunlight collection on the roof and distribution in the classroom

## 6.4 Interior light distribution on desk

Measurements were taken at the horizontal work-table considered to be 1.5 m distant from the collimator, on a full clear day with 75,000 lux exterior illuminance. Illuminance measurements (on sunny days) were taken with a light data-logger meter from 9h to 17h. The illuminance on the work-table ranged between 320 lux at 9h, 470 lux at 11h, 517 lux at 13h, 380 lux at 15h and 150 lux at 17h and it is shown in Figure 6.3. Figure 6.4, illustrates the

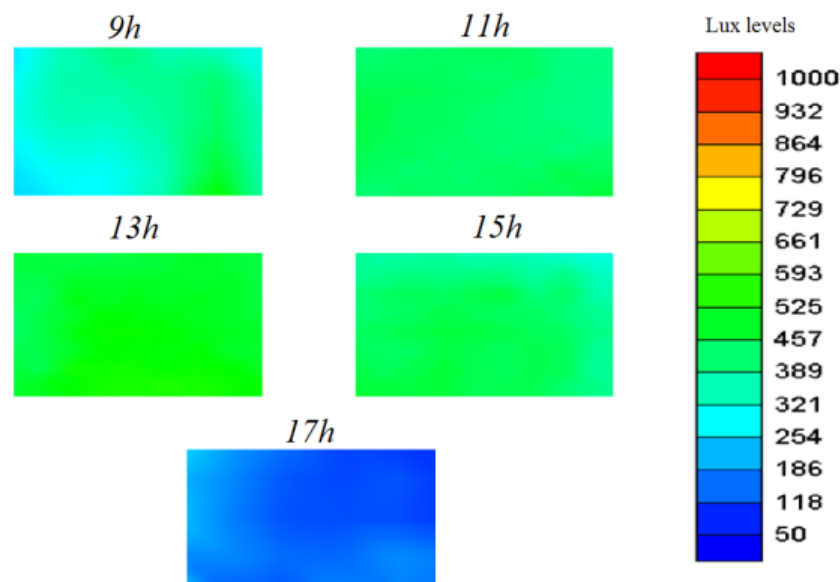


Figure 6.3: Light distribution on work-table

difference in illuminance levels before and after installation of the light pipe and collimator at 11h. Before installation the illuminance level on the work-table was 65 lux and after installation illuminance increased up to 470 lux. From the measurements, it can be seen that light distributed on the desk from 9 a.m. to 5 p.m is in the range (200 lux - 500 lux) required by the SABS for reading and writing (Table 1.1).

### 6.4.0.1 Daily and yearly light distribution model on the reading table in the classroom

Light distribution on the reading table from morning to evening and from January to December was established by assuming that the sky is clear throughout the year. The position of the sun in the sky varies continually during the day and also changes seasonally throughout the year. It is generally given as an azimuth (the direction of the sun) and elevation (the altitude of the sun) angles.

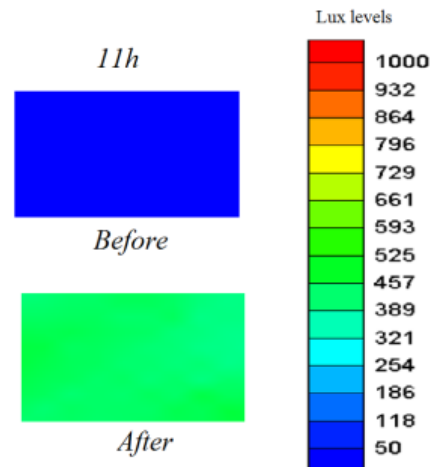


Figure 6.4: Illuminance levels before and after installation of light pipe and collimator at 11h

Ecotect analysis software (from Weather Tool) was used for the determination of azimuth and elevation angle of the sun on 1<sup>st</sup> February 2014 at the field test site (Table B.1 in Appendix B) and they are shown in Figure 6.6. Also Figures C.1, C.2 and C.3 in Appendix C also show the stereographic diagrams of certain hours (9h, 13h and 16h) on the same site. Figure 6.5 represents daily and yearly illuminance light distribution on the reading table. Cooking aluminium foil with a rough surface was used for the interior of the collimator.

## 6.5 Cost and value analysis of the daylight system

Prior to the analysis of cost and value of the light pipe and collimator, it is essential to give definitions of cost and value in this context. Cost is the price paid for a thing, object, service or utility. Value is the worth, desirability of a thing, object, service or utility or the qualities on which these depend. In most cases value can at best be estimated in an approximate manner. On the other hand, cost is a much more accurate measure. In this section a discussion on the cost and value of daylight delivered by light pipe and collimator is presented. The material on both cost and value ought to be taken as an indicative assessment owing to the infancy of this technology. Using the light pipe system in building as daylighting device can bring many benefits. The application of light pipe produces good value in terms of energy conservation, environment protection, maintaining health (physical and psychological) and improving productivity and work performance.

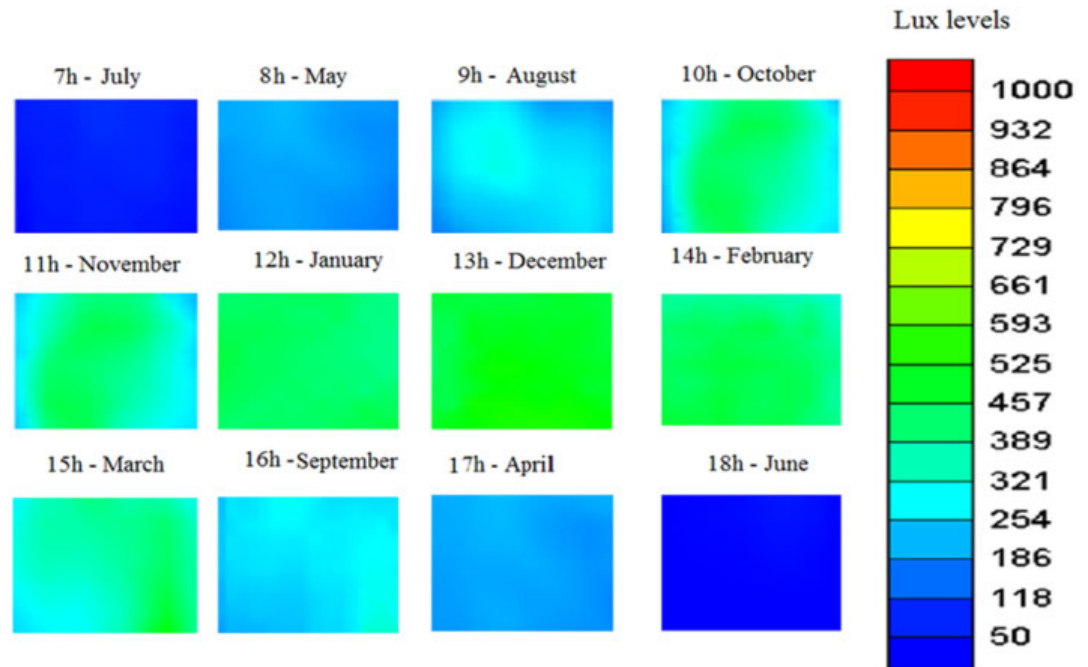


Figure 6.5: Daily and yearly light distribution on the reading table

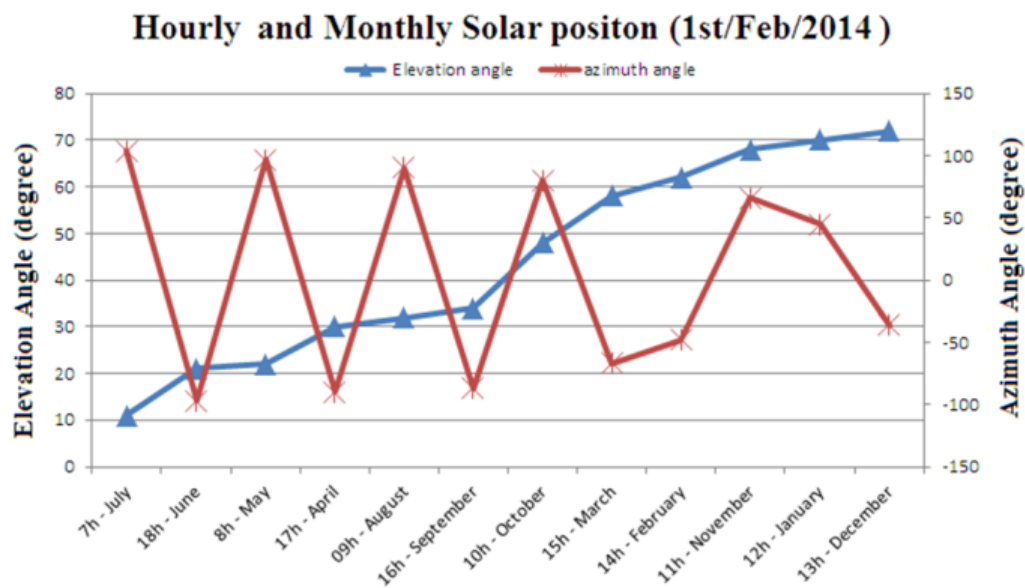


Figure 6.6: Sun's position at the experimental test site

### 6.5.1 Energy conservation

- Improvements in daylight penetration to the indoor environment, where better design can significantly lessen energy consumption on artificial lighting systems, and where lighting control strategies can improve class-



room performance.

- An economic cost comparison is to be carried out for the light pipe system and electrical lighting for classroom environments. The following data are available:

#### Conditions:

Room area:  $180 \text{ m}^2$

Design illuminance for electrical lights = 425 lux

Design illuminance for natural lighting = 350 lux

Life expectancy of Fluorescent tube = 8,000 hours

Number of fluorescent tube required = 18

Capacity of fluorescent tube = 30W

Working hours = 8 hours/day

Price of electricity including VAT = 7.22p/kwh

#### Environmental impacts

$\text{CO}_2$  emissions = 1030g/kwh-electricity

$\text{SO}_2$  emissions = 5.32g/kwh-electricity

$\text{NO}_2$  emissions = 3.51g/kwh-electricity

#### Light pipe

Number of light pipe system required = 5

Collimator prototype cost = R 10,000

Duplication cost of collimator = R 500 / each

Life expectancy of light system = 20 years

Minimum external illuminance required to provide an internal illuminance of 350 lux via use of light pipe = 50,000 lux

Table 6.1: Comparison cost based on ten-year cycle

Lighting System	No. of unit	Unit cost	Cost per year (Rand)	Cost in 10 years (Rand)
<b>Daylight</b>				
Light pipe	5	2000	10 000	10 000
Collimator Prototype	1	10 000	10 000	10 000
Collimator duplicated	4	500	2000	2000
Installation			1000	1000
<b>Total</b>			<b>23 000</b>	<b>23 000</b>
<b>Electrical</b>				
Fluorescent light tube	18	16	288	1152
Installation cost			400	1600
Wiring and fasteners			600	600
Running cost	18	31/day	11 384.5	113 845
CO <sub>2</sub> emission		4.4 kg/day	1.6 Tonnes	16 Tonnes
<b>Total</b>			<b>12 564</b>	<b>117 197</b>



From the comparison cost table above, light pipe system can reduce the electric consumption cost of the classroom by 79 % and also reduces 16 tonnes of  $CO_2$  emission in ten years.



Figure 6.7: Light distribution in the classroom at 9h a.m

Figure 6.7 represents the picture of how the classroom will look like at 9h a.m. if the whole classroom is installed by solar lighting pipe system figure C.6 (appendix C).

### 6.5.2 Health

Research has shown that daylight has an important effect on the human brain chemistry. Light entering via eyes stimulates the nerve centres within the brain that control daily rhythms and moods (Bill, 1999).

- People prefer environments with daylight conditions, and may recover from operations and illness more quickly in environments which are daylit, and which afford an exterior view.
- Buildings with a low daylight factor create environments with homogeneous lighting, having little contrast and holding limited interest for the occupant, whereas buildings with a high daylight factor transmit more quality daylight, creating conditions likened to those found externally, maintaining optimal mood conditions for longer.

- Typically people who are exposed to total daylight levels of greater than 2000 lux for only 90 minutes each day show positive mood symptoms. Light exposure is important to the inner time keeping of humans. Through evolution, man has adapted to rhythms such as body temperature to provide him with explicit knowledge of external time. The loss of this connection can contribute to fatigue, insomnia, and Seasonal Affective Disorder (SAD).
- It was concluded that light is an important factor in the well-being of building occupants and lack of it can have a deleterious effect on them.
- It has been reported that students within class-rooms do benefit from higher dosages of daylight in terms of increased performance and better general health.

## 6.6 Feedback from the users of the classroom about the light pipe and collimator system

Some eight people were asked questions about their opinions of the installed daylighting system and how they feel about it. They were 4 students, 2 lecturers, facility manager and the facility director all of them routinely use the classroom. The users acknowledged that:

- The levels of illuminance on the work-plane meet the lighting expectation and create a good visual environment,
- The presence of daylight will have a direct impact on well-being,
- The system will minimize the amount of artificial lighting and reduce electricity cost.

## 6.7 Summary

In this section, the performance of the passive light pipe system combined with collimator was assessed in a classroom. From the tests done it can be seen that the system distributed light uniformly on the work-table and that there was an average illuminance of 367 lux from 9h a.m. to 5 p.m. Also it was seen that if light pipes and collimators were fitted in the whole classroom a reduction of 79 % of electric consumption cost and 16 tonnes of  $CO_2$  would be reached in ten years.

## Chapter 7

# Discussion and Conclusion

### 7.1 General discussion

There is a link between light pipes and other core daylighting technologies and reduced electricity consumption because light from vertical windows at the exterior of the building will penetrate only a limited distance into the rooms adjacent to the exterior wall, and not at all into interior rooms. Hence the rear portion of exterior rooms and all interior rooms require advanced daylighting technology to obviate the need for electric lighting and this sector of daylighting presents unique challenges. The optical and physical aspects of redirecting and transporting light to the inner parts of buildings can be met by a number of technological means, but a primary barrier is cost. Light pipes are considered to be one of the most economical ways of transporting light and do not involve any moving parts or require much ongoing maintenance. As such, they hold considerable potential for daylighting in both existing and new buildings and both commercial and domestic buildings. This potential is being exploited with great success commercially by a number of companies worldwide and necessitates research into the various aspects of light pipe performance. The field of light pipe daylighting, however, is sufficiently advanced to permit investigation of more novel innovations in light pipe systems. The researcher found a way of increasing light output and controlling that output during experimental work.

#### 7.1.1 Dome solar collector

Improvements to the solar dome collector process have resulted in greater output from devices, and such improvements fall into two categories: traditional domes and innovative domes. Solar domes referred to as traditional, are generally manufactured from plastic material called polycarbonate. Polycarbonate domes are cheap but are not resistant to U.V rays, this leads to reduction of light permeability by up to 50 %. Plastic dome improvement might include its production from plexiglass material (type of plastic material which has

properties closer to those of glass). This material is resistant to U.V and has excellent optical characteristic of collecting sunlight and the ability to channel it in the tube. Use of plexiglass dome is limited due to its high price and low efficiency of gathering low angles sunlight.

For optimum performance and consistent daylighting throughout the year the traditional dome can be fitted with some technology such as; lenses or deflectors. A deflector inside the dome reflects and redirects the low angle light into the tube at a steeper angle of incidence. Light that would otherwise have passed straight through the dome and been lost will be redirected. In this research it was seen that dome fitted with a deflector increases illuminance by 30 % under diffuse light condition.

### 7.1.2 Light pipe materials

Manufacturers of reflective films have recently increased the typical reflectance of the product across the visible spectrum from 90 % to around 98 %. Because of the nature of light pipes, large numbers of reflections are inevitable, so that even small increases in reflectance result in large increases in output. High reflectance light pipes are now available commercially and it is expected that most if not all light pipe manufacturers will adopt these new films in the future. As found in the thesis research, they will enable pipes of the same size to give higher outputs, or pipes of a smaller size to give the same output, as well as extending the maximum length or aspect ratio that is permitted for a given transmittance. The improved film will allow pipes to be a third longer with no loss of output or to have a diameter a third less with no loss of transmittance. As optical properties are improved, however, light pipes will conduct more IR light into buildings as well as visible light. Most mirror films are very effective when reflecting near IR, meaning significant cooling loads in a warm room.

### 7.1.3 Light distributor device

Work on the light distributor component of the systems will be beneficial to users of light transport daylighting devices. The purpose of the light distributor element in the light pipe system is fourfold; diffusion of emitted light to give the desired spectral and physical distribution of light, glare prevention and effective reflectance of light to minimise loss. All these elements are related to the optical properties of the light distributor and will generally be dependent on one another. Increasing transmittance, for example, will increase glare if no measures are taken to prevent rays from exiting at low angles. The interrelation of these factors has led to a study of light collimator that should result in the optimisation of light distributor performance. A light collimator designed is a non-imaging optical system which focuses on transferring light efficiently and controlling its distribution, it has been designed according to the principle of edge rays that undergo one reflection (one-reflection map).

This collimator is chosen such that rays from the edge of the input aperture (tube exit aperture) are sent to the edge of the collimator aperture after one reflection. The light collimator interior is lined with cooking aluminium foil with a rough surface which transmits light in uniform surface brightness at all viewing angles.

## 7.2 Conclusion

There are many reasons for the utilization of natural light, but the major reason is a reduction in energy use leading in lower resource depletion and  $CO_2$  emissions. Moreover, well designed day-lit buildings have lower cooling loads where this is relevant, further reducing consumption, and occupants prefer natural where it is available. In schools the use of natural daylight doesn't only contribute to conservation of energy and reduction of greenhouse gases emission but has also been found to enhance the performance of children in schools. Even where the daylighting system is applicable due to the suitable climate, the majority of South African schools are more than ten years old, and were not designed with daylighting as a top priority. A need exists, therefore, to find an efficient means of improving the daylighting of existing schools. This researcher proposed PZLP as one of ways of improving daylighting in the existing schools.

The performance efficiency of PZLP was tested using plexiglass dome, a mirrored tube and polycarbonate prismatic diffuser. From the results, it can be seen that the plexiglass dome can collect up to 90 % of direct light (sunlight) and 70 % of diffuse light (skylight). As study on the improvement of dome efficiency for low sun's elevation angles (skylight conditions during, morning and dusk hours) was done and results from many readings over fourteen hours, revealed that a light deflector incorporated in the plexiglass dome increased illuminance under skylight by up to 30 % . From TTE results, it was seen that a mirrored pipe (of 1.6 ratio) transmits up to 90 % of direct light and 61 % of diffuse light collected by the dome. From measurements, it was also shown that TTE performs 31 % higher under direct sunlight conditions than under diffuse light conditions. Analysis results for interior illuminance distribution through the tube and polycarbonate diffuser, revealed that the light tube is not able to control interior distribution and that they produce inconsistent distribution with very low light levels on the work-plane (average of 45 lux from 9h a.m. to 5 p.m.). More uniform spatial light distribution was observed on the work-plane with the use of a diffuser but the light level was very low (average of 178 lux from 9h a.m. to 5 p.m) compared to the illuminance transmitted by the tube (25,000 lux).

The aim of the work on PZLP was to improve the yield of the device and this was achieved by incorporating light collimator in the light pipe design. A novel light collimator was used to increase the yield of the system up to the

average of 370 lux from 9h a.m. to 5 p.m. A light collimator is a non-imaging optical system which focuses on transferring light efficiently and controlling its distribution. Its design is based on the edge-ray principle. For uniform interior distribution the interior of the light collimator was lined with a reflector material using rough aluminium cooking foil. The daylighting system (PZLP combined with collimator) was seen to be cost effective as it decreased electric consumption costs up to 79 %, it is also environment friendly leading to reduction of 16 tonnes of  $CO_2$  in ten years. Furthermore, post installation tests and simulations were performed to test the stability of light levels for different altitudes of the sun and at different times of the year. It was found that the system provided acceptable levels between 9 a.m. and 5 p.m. even during cloudy winters with minimal shift from the geometrical centreline of the collimator.

# Appendices

## Appendix A

# Experimental Analysis of the Passive Zenithal Light Pipe

### A.1 Experiment test equipment

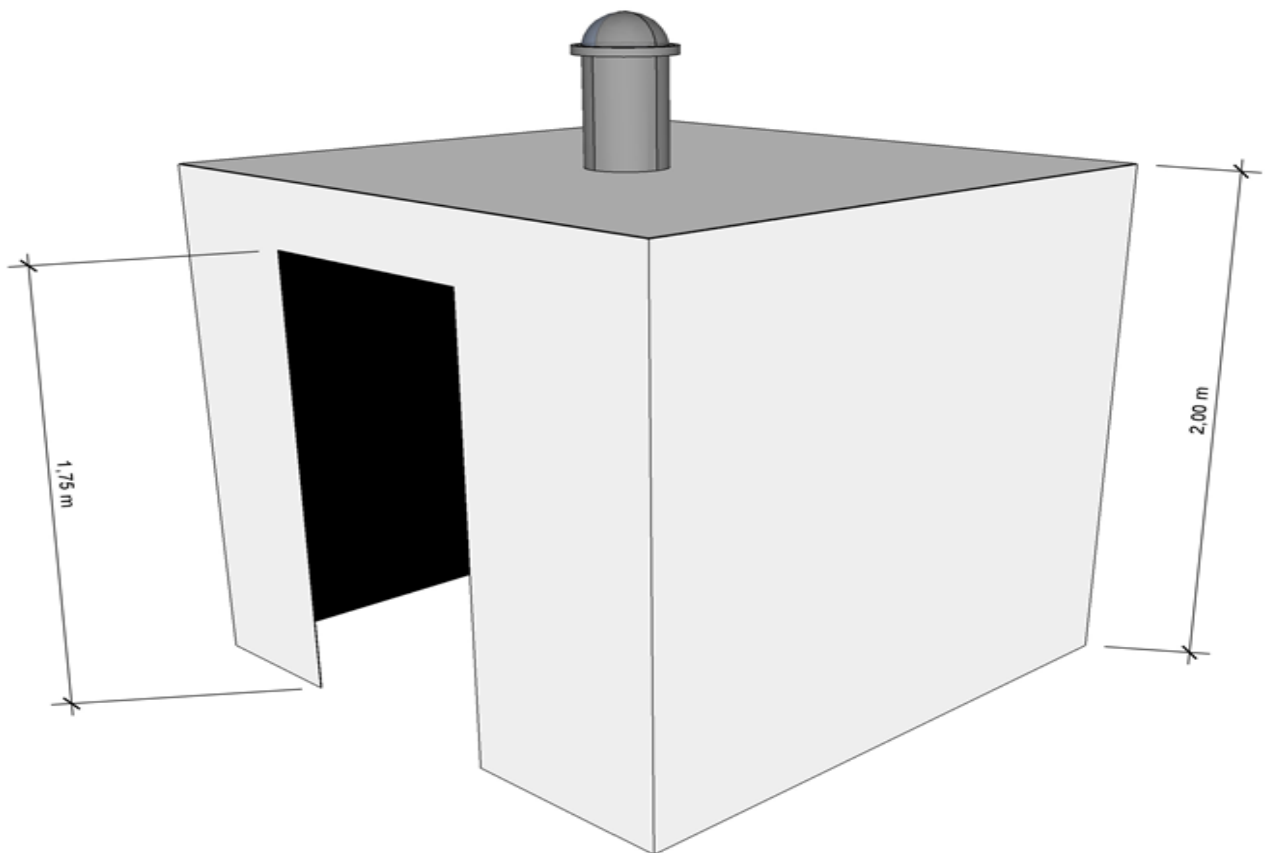


Figure A.1: Solar pipe installed in the sheet metal box



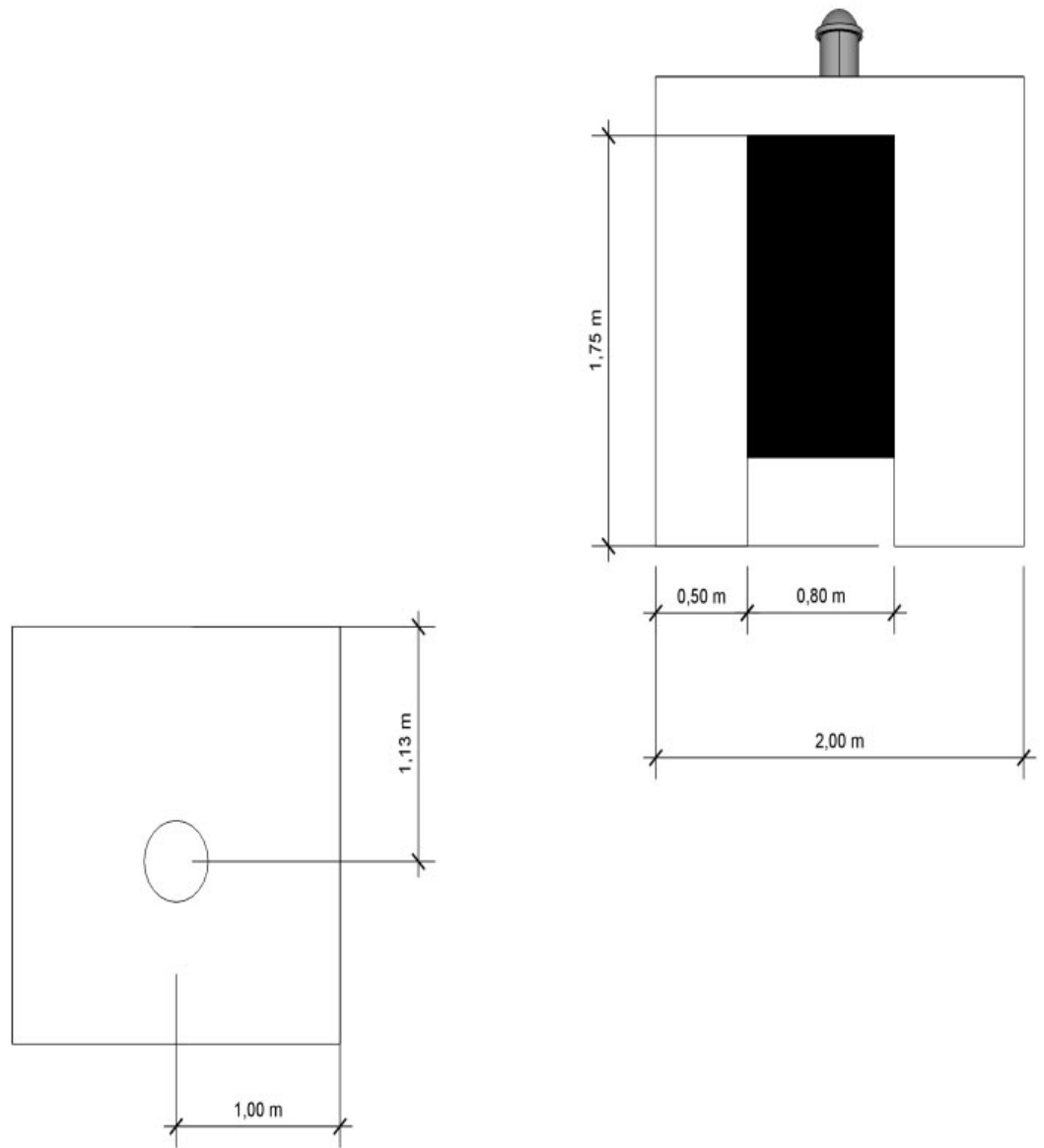


Figure A.2: Sheet metal box dimensions

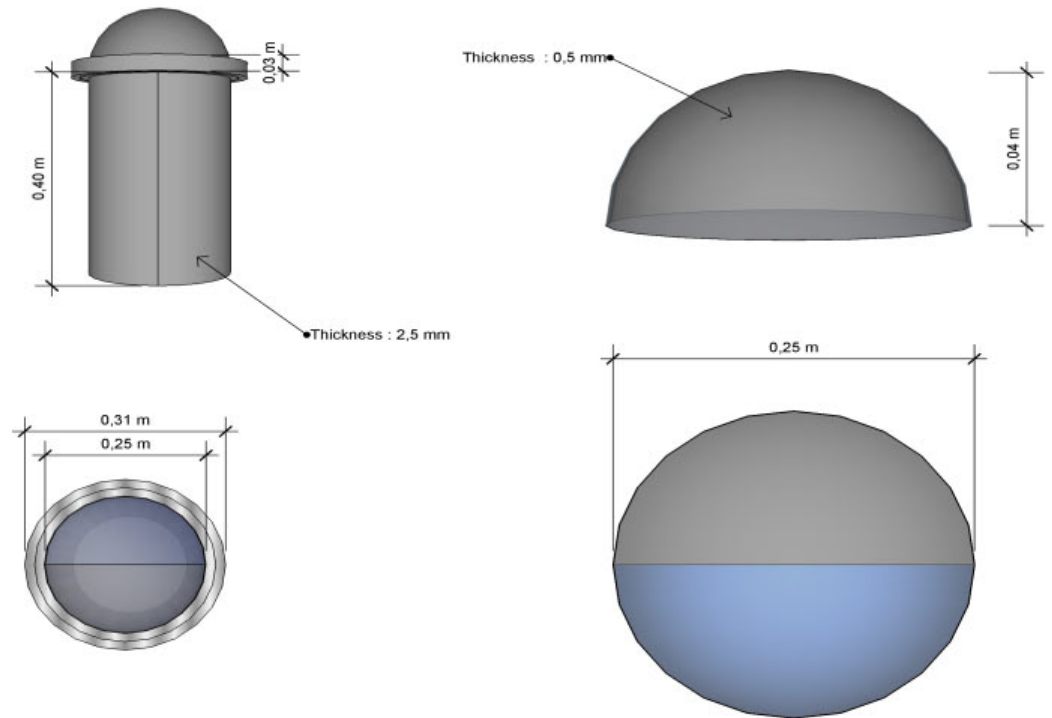


Figure A.3: Solar light pipe dimensions

## A.2 Dome collection efficiency

Table A.1: Collection efficiency of the plexiglass dome ( $\eta_{d1}$ ) under sunlight condition

Time (hour)	Measured $\eta_{d1}$ (%)			Average(%)
	June	July	August	
6	0	0	0	0
7	21	19	20	20
8	26	29	29	28
9	44	45	46	45
10	68	69	67	68
11	72	72	72	72
12	79	81	80	80
13	89	83	92	90
14	85	85	85	85
15	82	83	81	82
16	60	60	60	60
17	42	41	43	42
18	22	22	22	22
19	0	0	0	0

Table A.2: Collection efficiency of the dome ( $\eta_{d2}$ ) under skylight condition

Time (hour)	Measured $\eta_{d2}$ (%)			Average(%)
	June	July	August	
6	0	0	0	0
7	18	19	17	18
8	36	35	34	35
9	43	42	41	42
10	50	50	50	50
11	59	61	60	60
12	65	66	64	65
13	70	70	70	70
14	68	68	68	68
15	61	62	63	62
16	52	50	51	51
17	24	26	25	25
18	10	10	10	10
19	0	0	0	0

### A.3 Tube transmission efficiency

Table A.3: Incident angle ( $\beta$ ) and sun's elevation angle (Hs)

June			July		
Hours	Hs	$\beta$	Hours	Hs	$\beta$
6	4	86	6	2.19	87.6
7	15.5	74.5	7	12	78
8	26.5	64	8	25.5	64.5
9	39	51	9	37	53
10	51	39	10	49	41
11	63.5	26.5	11	61	29
12	74	16	12	70.5	19.5
13	77	13	13	75	15
14	70	20	14	69	21
15	58.5	31.5	15	58	32
16	46.5	43.5	16	46	44
17	34	56	17	34	56
18	22.5	67.5	18	22.5	67.5
19	0	90	19	0	90

Table A.4: Calculated TTE according to equation 4.1.3

Time (hour)	Calculated $\eta_{t1}$ (%)		Average(%)
	June	July	
6	0	0	0
7	54	45	49.5
8	70	69	69.5
9	81	80	80.5
10	87	86	86.5
11	91	90	90.5
12	94	92	93
13	95	95	95
14	93	93	93
15	90	90	90
16	85	85	85
17	77	77	77
18	65	65	65
19	42	42	42
20	0	0	0

Table A.5: Calculated TTE according to equation 4.1.4

Time (hour)	Calculated $\eta_{t2}$ (%)		Average(%)
	June	July	
6	0	0	0
7	33	25	29
8	52	51	51.5
9	67	65	66
10	76	72	74
11	84	82	83
12	90	88	89
13	92	90	91
14	88	87	87.5
15	81	81	81
16	73	73	73
17	62	62	62
18	47	47	47
19	22	22	22
20	0	0	0

APPENDIX A. EXPERIMENTAL ANALYSIS OF THE PASSIVE ZENITHAL  
LIGHT PIPE

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Table A.6: Measured TTE under direct sunlight condition

Time (hour)	Measured $\eta_{t3}$ (%)		Average(%)
	June	July	
6	0	0	0
7	22	18	20
8	46	38	42
9	60	56	58
10	68	64	66
11	71	69	70
12	84	80	82
13	90	88	89
14	74	72	73
15	66	64	65
16	55	47	51
17	30	20	25
18	0	0	0

Table A.7: Measured TTE under skylight condition

Time (hour)	Measured $\eta_{t4}$ (%)		Average(%)
	June	July	
6	0	0	0
7	18	12	15
8	38	34	36
9	43	39	41
10	50	46	48
11	54	50	52
12	56	54	55
13	63	61	62
14	52	48	50
15	47	45	46
16	25	25	25
17	11	9	10
18	0	0	0

APPENDIX A. EXPERIMENTAL ANALYSIS OF THE PASSIVE ZENITHAL  
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Table A.8: Data of TTE achieved by measuring ( $\eta_{t3}$ ) in comparison with the data calculated by equation 4.1.3 ( $\eta_{t1}$ ) and equation 4.1.4 ( $\eta_{t2}$ ) under direct sunlight

Hours	$\eta_{t1}(\%)$	$\eta_{t2}(\%)$	$\eta_{t3}(\%)$	$Dev._1(\%)$	$Dev._2(\%)$
6	0	0	0	0	0
7	49	29	20	14	6
8	69	50	42	6	5
9	79	66	58	9	5
10	86	74	66	8	5
11	90	83	70	4	9
12	92	89	82	2	4
13	95	91	89	2	1.4
14	93	87	73	4	9
15	90	73	65	12	5
16	85	62	51	16	7
17	77	42	25	24	12
18	65	22	0	30	15
19	42	0	0	29	0

## Appendix B

# Design, Fabrication and Testing of Light Collimator

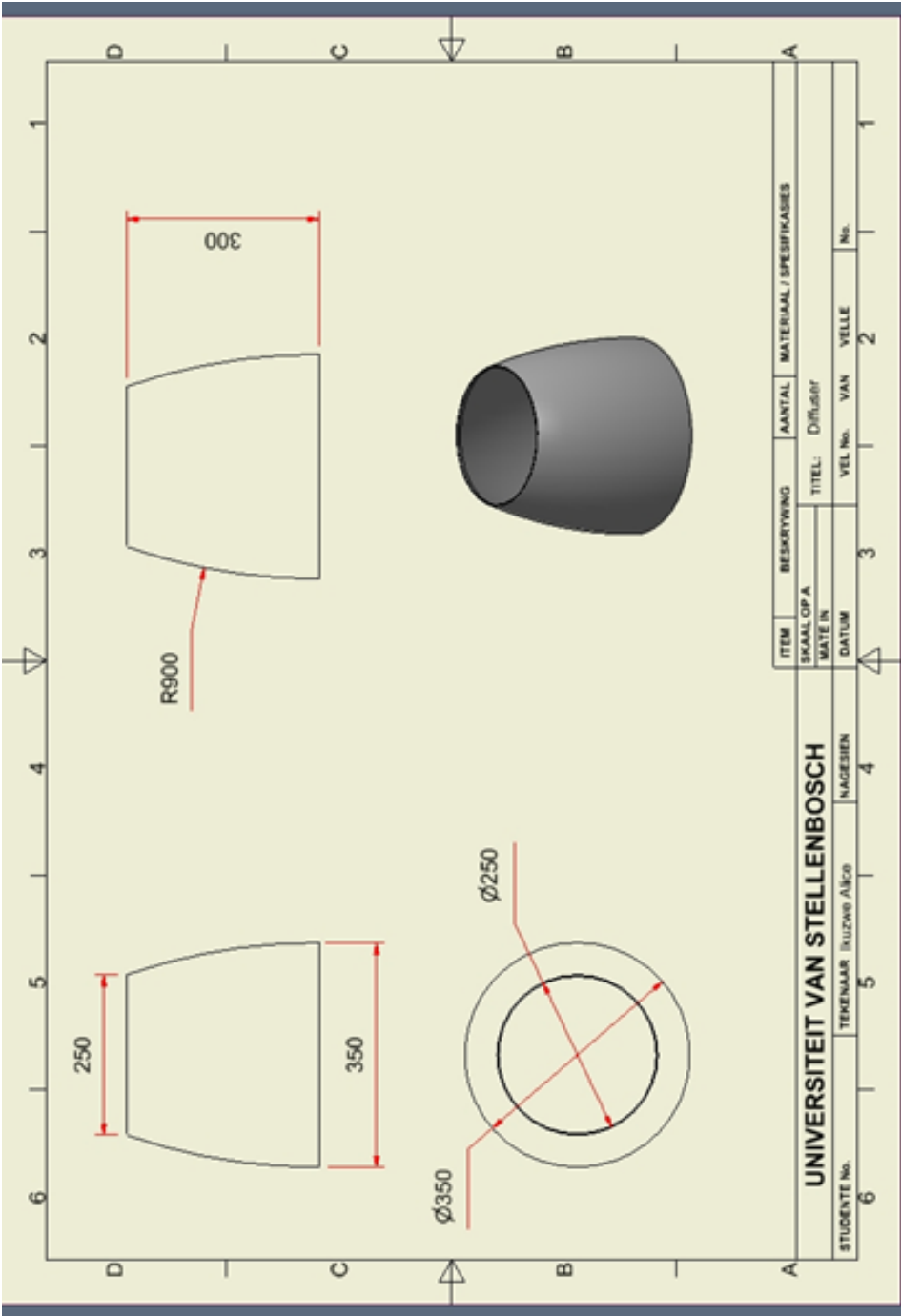


Figure B.1: Polystyrene light collimator



APPENDIX B. DESIGN, FABRICATION AND TESTING OF LIGHT COLLIMATOR

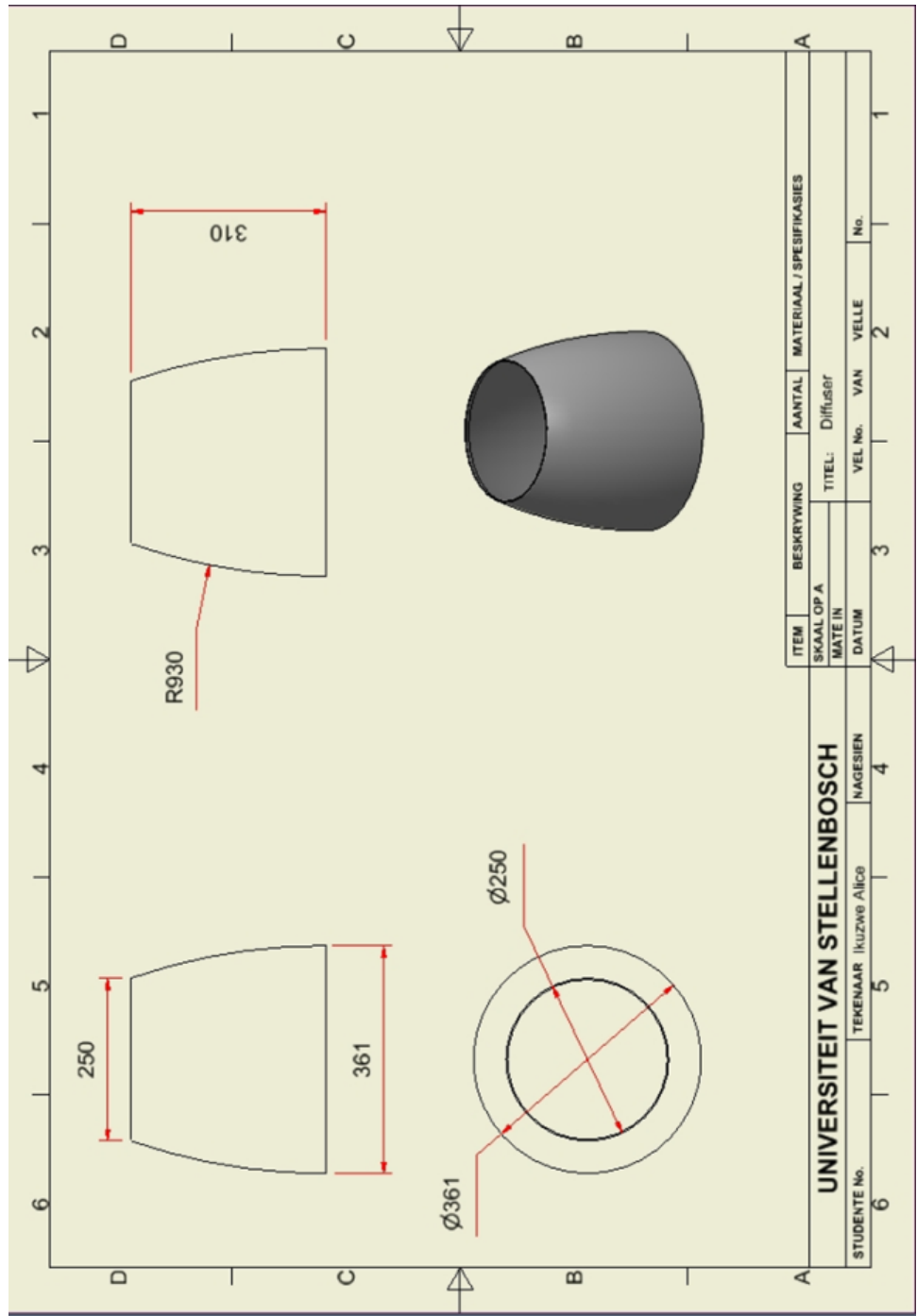


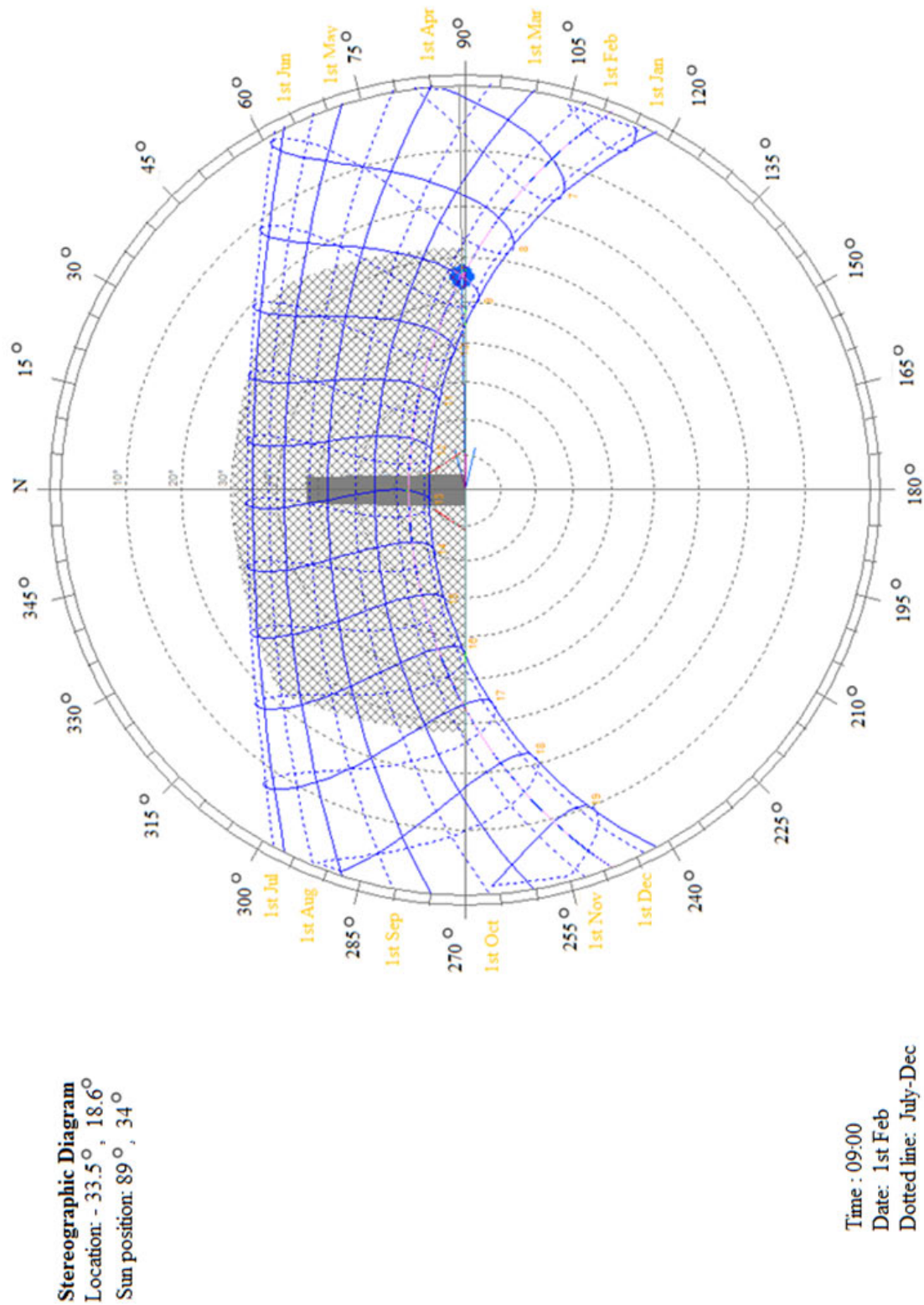
Figure B.2: Brushed aluminium light collimator

# Appendix C

## Field Test Site

Table C.1: Azimuth and elevation angle of the sun at testing place ( $33.5^{\circ}$  S,  $18.6^{\circ}$  E) on 1<sup>st</sup> February

Time and corresponding month	Elevation angle	Azimuth angle
7h - July	11	104
18h - June	21	-97
8h - May	22	97
17h - April	30	-90
09h - August	34	89
16h - September	34	-87
10h - October	48	80
15h - March	58	-67
14h - February	62	-48
11h - November	68	66
12h - January	70	45
13h - December	72	-36



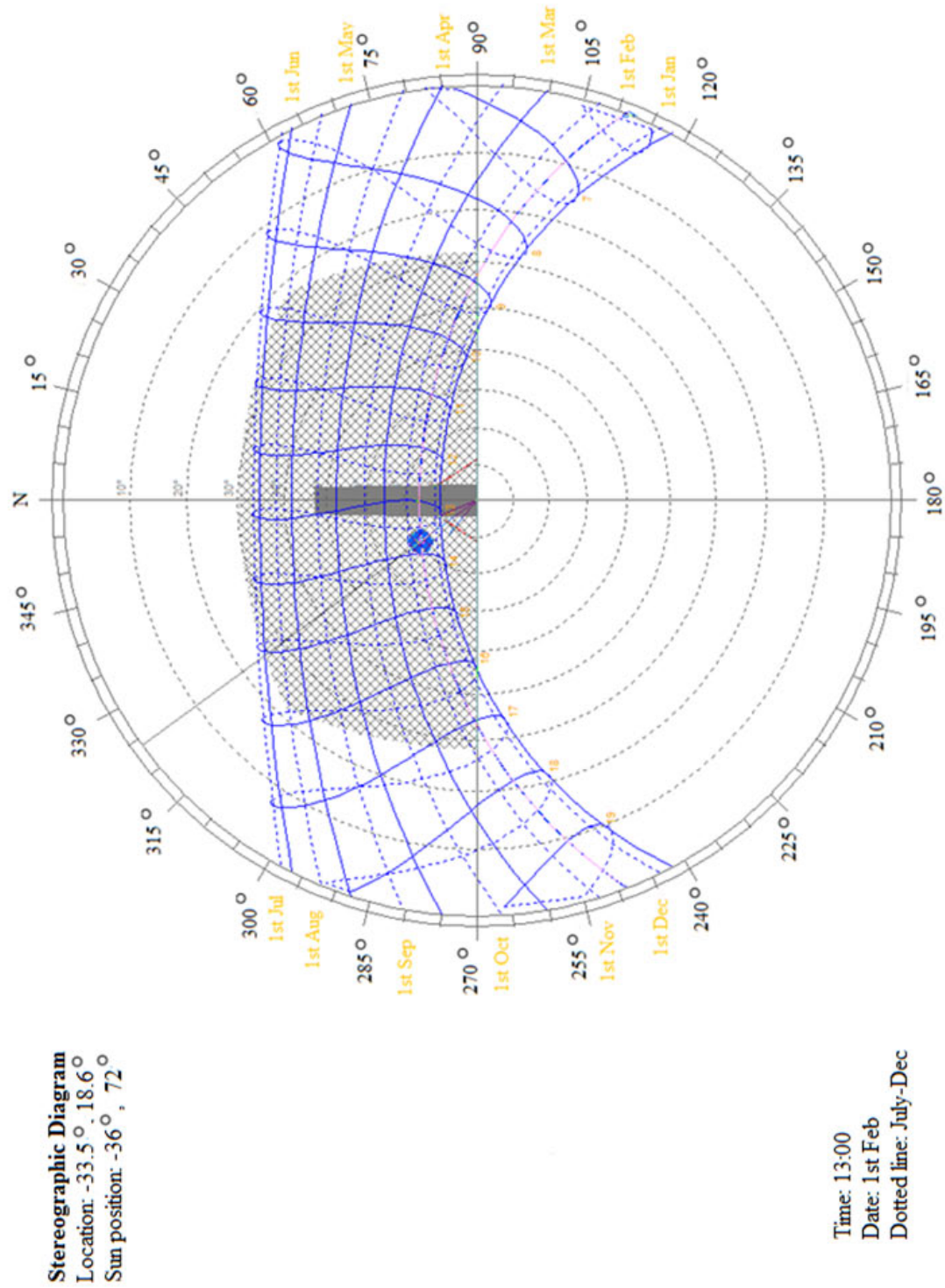


Figure C.2: Stereographic diagram at 13h00





Figure C.4: Elevation vs. azimuth angle

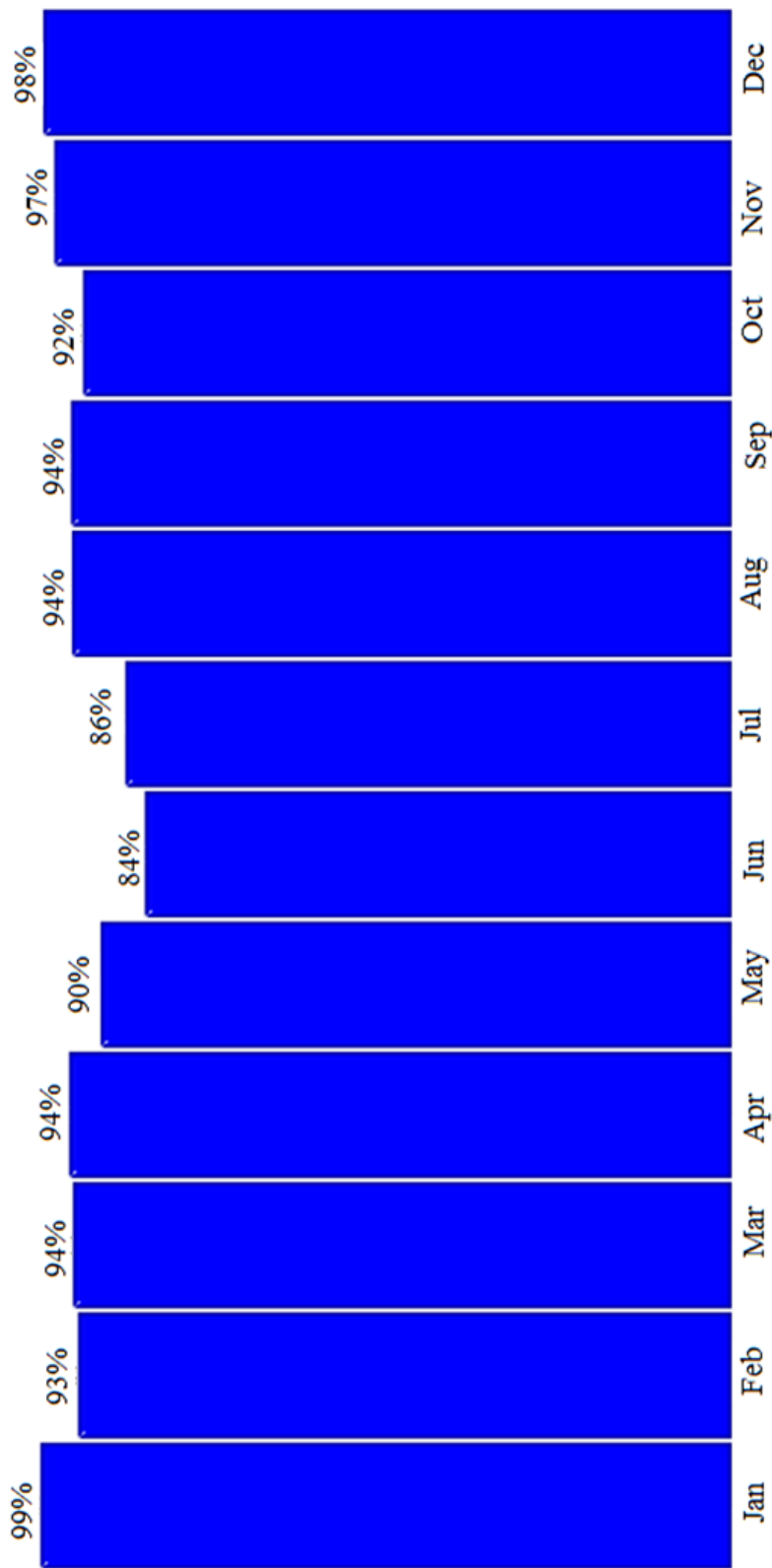


Figure C.5: Monthly solar access



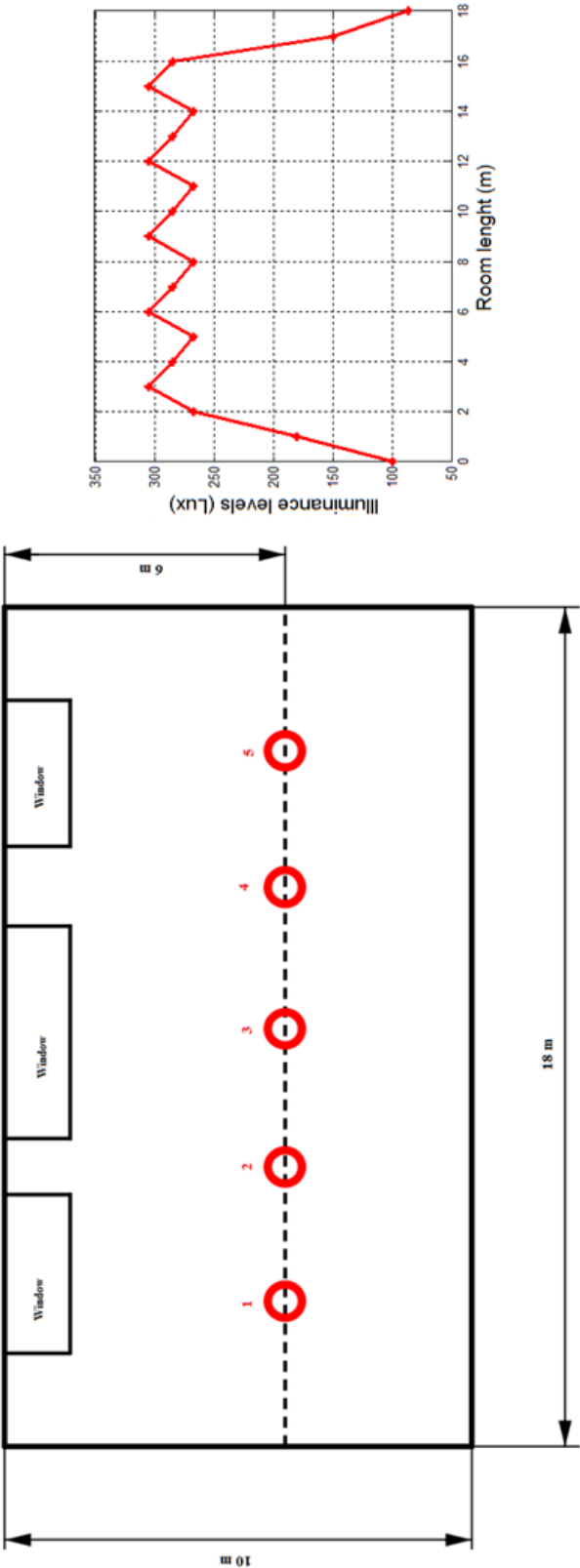


Figure C.6: Solar light pipe installed and light levels in the classroom



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